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DEVELOPMENT OF LOW-LEVEL TURBULENCE (LLT) FORECASTING METHODOLOGIES

December 1988

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A study has been carried out to investigate the improvement of low-level turbulence (LLT) forecasting. The literature review documents the current forecast problem as one of scale, that is, large-scale data are used to predict a small-scale phenomena. Although the current forecast procedures are objective at the level of the weather Central, the methods are simplistic and there is a high degree of subjectivity when the forecast is adapted to the local area. It was determined that significant improvements in forecasts can be made in the near future by improving local observations, communications, and developing computer based objective forecasting techniques. Finally, the LLT problem at Fort Irwin is documented and objective procedures are developed to improve LLT forecasts.

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1. INTRODUCTION

1.1 Background

The U.S. Army has an ongoing requirement for accurate and timely forecasts of low-level turbulence (LLT)* in support of the operation of helicopters and other low flying aircraft, especially in areas of complex terrain. Some recent reports of accidents and the loss of flying time during training exercises because of poor LLT predictions have defined a need to evaluate current forecast procedures and to determine whether the development of better techniques is feasible.

1.2 Objectives

As prescribed in the "Statement of Work (TCN: 87-597)," the objectives of the current study are "...to assemble a data base of concurrently measured surface and airborne turbulent intensities; compile a listing of all known forecasting methodologies for the prediction of mechanical, thermal, and lee wave turbulence; and utilize this existing information to develop practical and user-friendly prognostication rules for LLT occurrences that can adversely affect low flying aircraft.

1.3 General Approach

The objectives listed above were accomplished through information from a general literature review and a careful study of the current LLT forecast problem at the U.S. Army National Training Center (NTC) at Fort Irwin, California. The literature review was performed to isolate current and potential LLT forecast methodologies, to locate available data bases for the future development of improved statistical forecast techniques, and to investigate the applicability of artificial intelligence (AI) and related systems to the LLT forecast problem. The Fort Irwin study involved an on-site problem evaluation, the development of a prototype LLT forecast/nowcast system, and the development of a data base to test and further improve the proposed system. Finally, a series of recommendations have been developed on the basis of the combined results of the literature review and the NTC study.

2. TECHNICAL DISCUSSION

2.1 Literature Review

2.1.1 Background

The dimensions of those atmospheric motions that adversely affect aircraft in flight are a function of aircraft design and speed. Critical response scales commonly range from a few tens to a few hundreds of meters. In the atmospheric boundary layer, where there is often active turbulent exchange of heat and momentum between the surface and the atmosphere, the typical dimensions of turbulent eddies are proportional to the height above the ground; that is,

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*In this report "low-level turbulence (LLT)" is defined as bumpiness in flight within the planetary boundary layer.

they lie in the range of the strongest response for most aircraft. For this reason, and because of the slower speeds and restricted maneuverability of low flying aircraft, the prediction of LLT is one of the most important tasks for an aviation forecaster supporting for low level flight operations.

In the present section, the literature has been surveyed to determine: (1) the current state of the art of LLT forecasting, (2) the possibility of developing improved LLT forecast techniques, and (3) the applicability of AI to the improvement of LLT techniques.

2.1.2 Current LLT Forecasting Procedures

LLT forecasting procedures now in use recognize the inability of operational data networks to resolve mesoscale and microscale spatial and temporal characteristics of LLT. Therefore, with the exception of the occasional pilot report (PIREP), all current methods of LLT diagnosis and prognosis deduce LLT from the presence of some larger scale circulation which is assumed to generate LLT, or from the value of some large-scale parameter, such as a dimensionless number or index which is related theoretically or empirically to LLT (for example, Burnett, 1970; Lee et al., 1979; AWS, 1979; FAA, 1977; Mathews, 1985). A block diagram of the general LLT forecast procedure is presented in figure 1.

The strong dependence of LLT forecasts on the prediction or observation of specific larger scale circulations is emphasized in the literature by the separation of the majority of descriptions of forecast procedures according to the cause of the LLT (for example, FAA, 1987). The major causes are dry convection (thermals), moist convection (thunderstorms, downbursts, etc.), mechanical mixing, mountain waves, and fronts. Some of these "causes" occasionally overlap or are slightly ambiguous (for example, wind shear associated with large-scale fronts versus wind shear related to thunderstorm gust fronts); however, they are common categories that appear throughout the literature and will help focus the discussion to follow.

In figure 1, pattern recognition generally refers to the identification of synoptic weather patterns that support the occurrence of one or more of the causes of LLT listed above. Favorable large-scale patterns for moist convective phenomena are well-described by Miller (1972), Doswell (1982, 1985), and Ray (1986). Those patterns that support widespread dry convection are discussed in detail in the literature related to forecasting for gliding (for example, see Lindsay and Lacy, 1976; Bradbury and Kuettner, 1976; Wallington, 1966).

Synoptic patterns that are conducive to strong winds and mechanical mixing have been described extensively for the continental United States, by Waters (1970). Patterns associated with mountain wave turbulence are generally well-known and have been summarized by Alaka (1960), Nicholls (1973), and many others. Large-scale frontal patterns are also well-known from the general meteorological literature (for example, Petterssen, 1956; Palmen and Newton, 1969; Keyser, 1986).

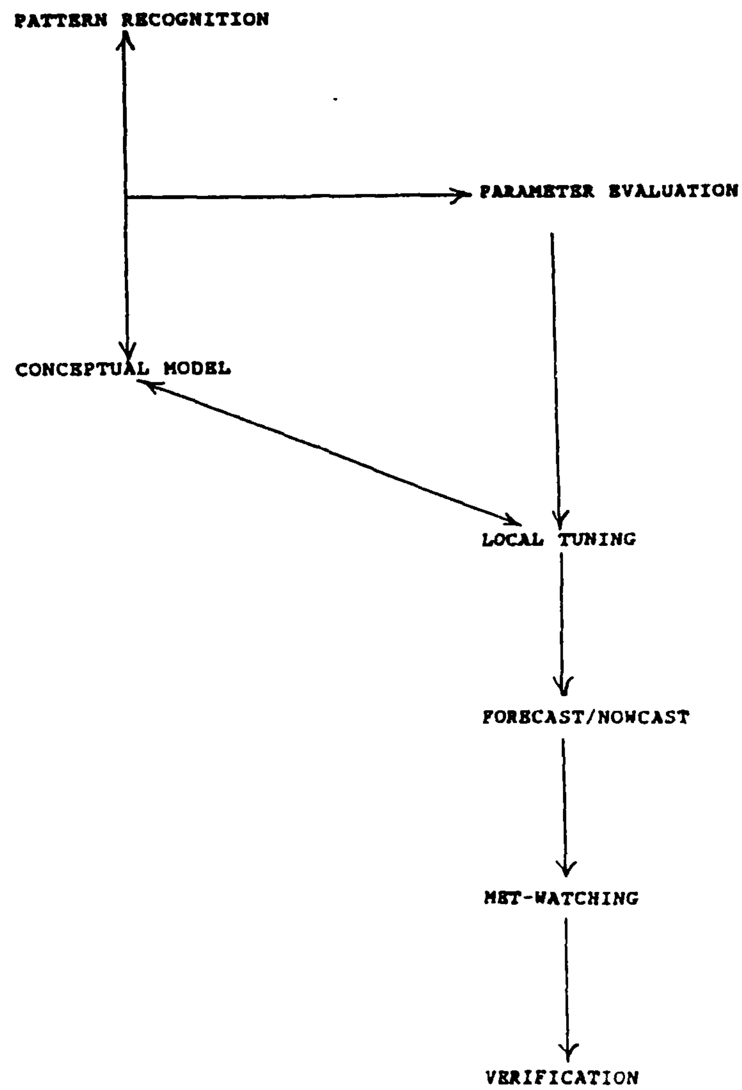


Figure 1. Low-level turbulence forecast procedure.

A potential source for the documentation of synoptic patterns associated with LLT are terminal forecast manuals (TFM) for base weather stations. Examples for the Fort Irwin area are the NTC Forecaster Handbook (1987), Farnham and Gould (1956), and Farnham and Vercy (1969). A general listing of TFMs is given in AWS publications TC-85/001 (1985).

A conceptual model (figure 1) is defined here as a mental picture of a mesoscale phenomenon that allows the forecaster to deduce the unobserved LLT from the well-observed larger scale pattern. It aids the forecaster in the integration of sparse data into a coherent mesoscale/microscale pattern. The individual model is usually a mesoscale circulation; it may be based on theory or on an average of special field observations, or simply on experience.

Probably the best example of such a model is the thunderstorm (Palmen and Newton, 1969; Atkinson, 1981; Doswell, 1982, 1985; Kessler, 1985; Weisman and Klemp, 1986; Fujita, 1985) in which LLT is associated with downbursts, gust fronts, wind shears, and related phenomena. Models for dry convection are discussed extensively in the soaring literature cited above, and by Scorer (1978). Most conceptual mountain wave models used currently by forecasters are a product of the Sierra Wave Project (for example, see Alaka, 1960, for a summary). More recent publications by Nicholls (1973), Lester and Fingerhut (1974), Lilly (1978), and Durran (1986a) have dealt with models of mountain wave systems that produce Strong Downslope Windstorms (SDW). Conceptual models used by forecasters for deducing mechanically induced LLT or for determining the presence of LLT in the vicinity of fronts (aside from gust fronts) do not have a clear mesoscale component.

In figure 1, parameter evaluation refers to the process of quantifying the LLT nowcast/forecast by determining the values of critical parameters. In the automated forecast (for example, at a weather central), this step is accomplished first. That is, once the required data have been acquired and analyzed, all "critical parameters" may be evaluated by computer, assuming they lend themselves to computation at grid points. This, of course, produces a nowcast. A similar evaluation may be done with predicted fields. If the forecast process is manual (for example, at a local forecast office), the parameter evaluation usually follows the pattern recognition step (figure 1).

Parameters currently used in LLT prediction are of three types: the basic meteorological variables, their temporal and spatial derivatives, and certain combinations, such as physical and/or empirical indices, and some measure of terrain roughness. Some of the most common parameters are listed in table 1. Those parameters associated with the prediction of LLT associated with moist convection are extensive and well-known, and are not listed here. See Miller (1972) and Ray (1986) for the discussion of a wide variety of parameters, indices, and other forecast tools (radar and satellite information) useful in the diagnosis of LLT and wind shear associated with moist convection.

Forecast aids for LLT associated with large-scale fronts generally depend on some measure of the intensity and speed of the front. Richwien (1979) indicates that a front with a horizontal temperature difference of at least 10 °F and moving at 30 knots or greater is associated with significant LLT. Also, it is well-known that fronts moving across rough terrain are almost always associated with LLT.

Smaller scale sea breeze fronts and convergence zones not associated with thunderstorms are known to produce significant lift for gliders (Wallington, 1966); therefore, they may be a source of LLT for some types of aircraft. Again, the soaring literature provides excellent guidance in the prediction of those phenomena (for example, Bradbury and Kuettner, 1976).

TABLE 1. COMMONLY USED LLT FORECAST PARAMETERS

DRY CONVECTION (THERMAL) LLT	
	Air temperature
	Temperature lapse rate
	Potential temperature lapse rate
	Thermal Index
	Showalter Index
	Richardson Number
MECHANICAL LLT	
	Surface wind speed and gusts
	Gradient level wind speed
	Mountain top wind speed
	Terrain Roughness
	Global Weather Center (GWC) nomograms
MOUNTAIN WAVE LLT	
	Mountain top wind speeds
	Cross mountain SLP gradient
	Rate of decrease of Scorer Parameter with height
	Harrison nomogram
LLT INDICES	
	Burton's Turbulence Index (BTI) = f(wind, stability, pressure tendency, and roughness)
	GWC Mechanical Turbulence Index = f(wind, roughness)

Critical values for the various parameters listed in table 1 are a function of the geographical area, the time of day and the year, and the aircraft category. Many values are listed in Lee et al. (1979), AWS (1979), and FAA (1987). The most frequently quoted lower threshold value is 20 knots for mountain waves and low-level mechanical turbulence significant to aircraft operation. At the upper end of the scale, 50 knots corresponds with severe turbulence in all cases, although for some aircraft the threshold is significantly lower (35-40 knots). Jones et al. (1970) have completed an extensive evaluation of the use of wind speed, lapse rate, roughness, BTI, RI, and Showalter index with LO-LO CAT data. Their results indicate the importance of wind speed, roughness, and stability and the utility of BTI in diagnosing and predicting LLT.

For the most part, rules of thumb for LLT forecasts/nowcasts are primarily numerical, that is, related to the parameters listed in table 1. Those values are listed in the previously cited references. Several rules of thumb are available for specific localities; they are usually found in TFMs, alerting local forecasters to turbulence prone areas. A useful summary of general rules of thumb is given by FAA (1977) in a table entitled "Locations of probable turbulence by intensities versus weather and terrain features." Some other useful rules, common throughout the literature in one form or another, are the intensity of turbulence always increases with wind speed and roughness and the turbulence elements (hence surface gusts and LLT) have dimensions proportional to the size of the roughness elements.

In figure 1, local-tuning refers to the procedure of adapting the centralized LLT forecast/nowcast to the local area. It requires a careful evaluation of the centralized product. Local parameter evaluation (table 1), PIREPS, and rules of thumb are introduced to tailor the forecast to the needs and limitations of the local user. Many rules of thumb are specialized for a particular locale.

"Met-watching" is the common term for monitoring a critical situation once the forecast/nowcast has been made. In critical evaluations both local-timing and met-watching are labor-intensive (Richwien, 1979).

Finally, as with any comprehensive forecast scheme a systematic verification is carried out to monitor the skill and improve the quality of LLT forecasts (McGinley, 1986); this step is often unsatisfactory because of the few verification reports from aircraft.

2.1.3 Future Improvements in LLT Forecasts/Nowcasts

As illustrated in the preceding section. current procedures of LLT forecasting/nowcasting are based primarily on the established relationship of the various "types" of LLT to certain large-scale patterns via conceptual mesoscale models via the quantification of those patterns using available data, and via the experience and attention of the local forecaster. There are several obvious problems with this scheme. Although the synoptic patterns associated with LLT are well-known, the use of conceptual mesoscale models is problematic. Most of the conceptual models currently brought to bear on the operational problem are "mean" or "typical" two-dimensional pictures of phenomena that have large spatial and temporal variabilities. Therefore, there will be many situations that they describe poorly. Also, there appears to be a wide variation in the understanding and application of these models by forecasters. The pattern evaluation step can overcome some of these problems, especially when that step is accomplished objectively. Currently, such quality control can be assured only at a weather central. Sooner or later the LLT forecast will reach the local forecaster and subjectivity will be introduced when the forecast is tailored to the local area.

The final serious problem that plagues LLT forecasts/nowcasts is lack of data. Even objective pattern evaluation procedures suffer from the lack of a very extensive or sophisticated data base. Aside from the use of a few semi-quantitative PIREPS, none of the current procedures is based on direct measurements of LLT.

This section of the report describes an examination of the literature that was performed to determine whether recent research, especially in the areas of the

LLT causes discussed above, could be adapted to improve LLT forecasts. Specifically, the possibility of improving the model/parameter components of the LLT forecast procedure was considered.

During the last 10 years, major progress has been made in the areas of mesoscale observations and mesoscale modeling. Thus more and more detailed descriptions of a wide variety of mesoscale circulations have become available.

Two recent reviews are available in texts on mesoscale circulations: Pielke (1984), which covers especially modeling studies done in the United States up to the early ASCOT papers, and Atkinson (1981), which provides a somewhat broader treatment of mesoscale research conducted in Europe and Asia as well. Both texts discuss mathematical models of mesoscale circulations; Atkinson (1981) also summarizes much observational data. In addition, Ray (1986) covers much the same material from a forecasters perspective. Three overviews of "Mountain Meteorology" are also available: GARP (1978), Smith (1979), and Heister and Pennel (1980).

Probably the most usable results of recent mesoscale research are those from studies of moist convection. As indicated in the last section, much of the recent information on gust fronts, outflow boundaries, downbursts, and related phenomena have been adequately reviewed in recent works by Doswell (1982, 1985), Fujita (1985), Ray (1986), and many others. The relative ease of observation of those phenomena (compared, for example, to mechanical turbulence) and their role in several fatal and well-documented aircraft accidents (for example, Fujita, 1978, 1986) likely accounts for the rapid assimilation of the new information by the forecast community. This is not the case for progress made in other areas of mesoscale research.

With the exception of the use of satellite imagery to locate regions of mountain lee wave activity and the development of a number of strong downslope windstorm (SDW) prediction aids (for example, Brown, 1986), few dramatic improvements have been made in the prediction of mountain waves in the last 25 years (also see Durran, 1986). This situation exists despite an intense research effort that has greatly improved our understanding of those phenomena (for example, GARP, 1978; Smith, 1979; Heister and Pennel, 1980; Mass and Albright, 1985; Kuettner, 1986).

Information that has evolved from research but still awaits application to the LLT problem includes the extension of the simple lee wave model (Alaka, 1960), to include the SDW type (Lilly and Zipser, 1972; Lester and Fingerhut, 1974), a better understanding of the dynamic causes of SDW (Klemp and Lilly, 1975, 1978; Peltier and Clark, 1979; Smith, 1985; Durran, 1986b), and the further use of satellite data to diagnose SDW in some areas (Elrod, 1986; Lester and Bach, 1986).

Although SDW theory has been advanced significantly, none of the current models have been adapted to the prediction of the details of SDWs and associated LLT in an operational setting. However, there are some parameters from SDW theory that may be useful in development of new LLT forecast tools. Several of the theoretical studies noted above have emphasized the importance of the steepness of the lee slope of the mountain in the production of SDWs. Although this requirement was documented many years ago (for example, see

Harrison, 1966) for the production of strong lee waves, and by Scorer (1978) and many others for the separation of flow over a ridge, no specific application was encountered in the LLT prediction methods reviewed to date. The ability of microcomputers to manipulate and display detailed terrain data bases locally indicates that the time is right for the local forecaster to make good use of that information.

Brinkmann (1975) and Giusti (1987) have shown that the stable layer which is always present above the mountain tops during mountain wave events is significantly stronger during SDWs. Klemp and Lilly (1975) have shown that if the atmosphere is approximated as a three-layer hydrostatic model, and disturbed by a mountain, strong surface winds will be produced in the lee in proportion to the amplification factor

$$AMP = N_1 \times N_3/(N_2)^2$$

where N_1, N_2, and N_3 are, respectively, the Brunt-Vaisalla frequencies for the stable layer at and below mountain top, the upper troposphere, and the stratosphere. Other factors such as the dimensions of the layers, the vertical wave lengths of the lee waves, and the mountain height are important, but current work by Lester, Bach, and Muranaka (1988), suggests that AMP evaluates an important contribution of SDW. Giusti and MacKay (1988) are currently investigating the predictive value of AMP via regression techniques.

Recently, Muranaka (1988) used a microcomputer to apply the mass consistent wind model developed by Ludwig et al. (1985, COMPLEX), to the analysis of the surface wind distributions during two SDWs over the foothills of the Canadian Rockies. The results showed promise for operational use, and it was recommended that further experimentation be made with a simple two-dimensional lee wave model as the upper boundary to determine whether the COMPLEX can be used practically, to generate nowcasts of surface winds and, thus, LLT.

In dealing with LLT due to the flow of stable air over complex terrain, one of the considerations is the nature of eddies downstream of individual barriers. These phenomena include hydraulic jumps, horizontal meanders, and turbulence wakes in the lee of hills and other terrain obstruction. The Froude number (F) is a dimensionless number that lies in certain critical ranges when the flow takes on certain unique characteristics. F is defined as

$$F = U(NL)^{-1} \quad ,$$

where U is the undisturbed fluid velocity, N is the Brunt-Vaisalla frequency, and L is a characteristic obstacle dimension (for example, the height). Baines (1987) has recently given an extensive review of the interpretation and application of the Froude number. F may be useful for LLT diagnosis in complex terrain since its calculation does not involve any assumptions that would be invalidated by nonuniformity (unless, of course, some "bulk" F was estimated for a large area). Since the measure is taken upwind of an obstacle, local instabilities may affect the airflow which would not be predicted by the Froude number. Some typical studies that have used F are listed in table 2.

TABLE 2. TYPICAL STUDIES THAT HAVE USED THE FROUDE NUMBER

Manins and Sawford (1982)	Found a critical Froude number of 1.6, above which the synoptic flow would flush the small valley where the study was held. Concluded that the critical Froude number would be terrain dependent.
Furman and Wooldridge (1984)	Calculated Froude number for flow around and over an obstacle. Found a value of F = 0.09 for very stable flow around the hill. For flow that just begins to go over the hill an F = 0.4 was calculated; for smooth flow over the hill F > 2.0. The authors conclude that the flow over the hill at the lower Froude number was caused in part by an unstable region of the windward base of the hill which did not affect the Froude number.
Wooldridge and Furman (1984)	Observations of a simple hill and flow parameterized by Froude number. For values 0.3 < Fr < 0.7 superpressured balloons passed around the hill and were occasionally caught in a lee-side rotor which was not present at higher Froude numbers.
Smith (1984)	Calculated Froude numbers for observed flows. Conclusions tentative.

As discussed earlier, the treatment of mechanical turbulence in current LLT forecasts does not depend on a conceptual model beyond a simplistic idea of random eddies that become stronger as the wind increases and/or the terrain becomes rougher. The improvement of instrumentation coupled with the increase in the study of the transport and diffusion of pollutants has lead to a much better understanding of the small-scale flow features that develop near land-sea boundaries, and complex terrain. Many details are found in Atkinson (1981) and, with respect to numerical modeling, in Pielke (1984). The specific details for individual studies vary widely as a function of the terrain. Examples of some of those details are shown in Table 3.

TABLE 3. MECHANICAL TURBULENCE STUDIES DETAILS

Mahrer and Pielke (1978)	Sea breeze with onshore synoptic winds.
Bornstein and Thompson (1981)	Sea breeze front retardation.
Yoshikado (1981)	Synoptic scale influence on sea breeze.
Lyons (1972)	Climatology and prediction of sea breeze.
Lyons (1975)	Turbulent diffusion at shoreline.
McCarthy and Young (1978)	Profile (structure) of New England coastal front. Authors note that the front, once understood, is quite predictable. This could well be true of many local phenomena.
Manis & Sawford (1979)	Model of katabatic winds.
Dickerson & Gudiksen (1981)	ASCOT report (Geysers studies).
Neff and King (1985)	Studies using acoustic sensors (ASCOT).
Porch et al. (1988)	Contributions of valley tributaries.
Stone & Hoard (1988)	Side wall circulations and flow surges.
Whiteman (1988)	Vertical profiles of downslope.
Whiteman (1982)	Observed vertical and cross valley structure using tethered balloons.
Whiteman & McKee (1982)	Observed inversion breakup and provided time estimates based on inversion structure.
Segal et al. (1986)	Observations and modeling of the effect of cloud shading on sea-breeze and upslope winds.
Wooldridge & Orgill (1978)	Momentum flux over mountain valley, observations of synoptic scale flow penetrating the top of a valley.
Selvam et al. (1983)	Discussion of the mechanism by which rotor circulations are maintained.
Baker et al. (1984)	Importance of angle of ridgeline to flow.
Etling and Wamser (1988)	Structure of vortexes in lee of islands.

Since one of the causes of LLT is dry convection, it has been recommended by some scientists that the application of some of the basic boundary layer stability criteria such as Pasquill stability class, Richardson Number, and Monin-Obukhov Length (for example, Munn, 1966; Haugen, 1973) be considered as LLT forecast parameters. Pasquill noted that the downwind spread of a plume or puff was dependent on the distance from the source and the stability of the atmosphere in the area as long as one had some knowledge of the behavior of the atmosphere in general. In order to treat such boundary layer influences objectively, he (Pasquill 1961) developed a set of diffusion curves. The curves were derived from experiments carried out over relatively smooth rolling terrain. Stability conditions are estimated from "surface" windspeed and daytime insolation (a very general measure of the temperature profile). For each stability class a curve is drawn relating the horizontal or vertical dispersion of a scalar quantity to the distance from the source.

Extension of this kind of study into complex terrain was complicated by the fact that mountain valleys tended to form extremely stable layers during the night and that the daytime mixing generally exceeded that estimated by the Pasquill curves for similar conditions in flat terrain (for example, Koch et al., 1977). In addition, small-scale convergence zones and return flow situations made the estimation of diffusion much more difficult. Even with the application of quantitative means to estimate stability, this categorization of turbulence has not proven to be valid for complex terrain where there is often a gradient in stability and wind velocity and therefore in turbulence.

It should also be noted that for air pollution concerns, once the atmosphere is "well mixed" there is no further need to categorize turbulence. Since, according to the Pasquill stability classes, this occurs at a windspeed of 6 meters/second, in our opinion these categories have little bearing on turbulence encountered during aircraft flight, even for light aircraft.

The flux Richardson Number (R_f) is defined as

$$R_f = \frac{K_H}{K_m} R_i ,$$

where K_H is the eddy diffusivity for heat, K_m is the eddy diffusivity momentum, and R_i is the gradient Richardson number given by

$$R_i = \frac{g}{0} \frac{\partial 0}{\partial z} \left(\frac{\partial u}{\partial z} \right)^2 .$$

In the last equation, g is gravity, 0 is potential temperature, and u is windspeed. Richardson (1920) derived the expression for R_f for "just turbulent" flow in horizontally homogeneous conditions. R_i may be related to the Monin-Obukhov scale length, L (Monin and Obukhov, 1953; Panosky and Dutton, 1984) as

$$L = \begin{cases} z/R_i , & R_i > 0 \\ (1-5R_i)z/R_i , & Ri > 0 \end{cases}$$

The flow is better characterized by L since R_i is a function of height (z). The similarity theory is that the boundary layer expands or contracts with L (Munn, 1966). During the daytime, the ratio (-z/L) represents the relative importance of heat convection (-z/L strongly negative), mechanical turbulence (z/L approximately zero), and, at night, the suppression of mechanical turbulence (z/L strongly positive). Thus the function z/L yields more information about the type of turbulence over its entire range of values. R_i on the other hand simply exceeds some finite critical value for the onset of the turbulence. The application of either L or R_i to the characterization of LLT on an operational basis is questionable because of the poor quality of observations normally available. Furthermore, in areas of complex terrain, the representativeness of these variables is in doubt.

Although many studies and models of mesoscale circulations exist, few are operationally useful predictive numerical models. Most are diagnostic, and while they can increase understanding of the mechanisms that drive the circulations they do not provide real-time, operational forecasts. Prognostic models such as the work done by Yamada (1981, 1983) are very detailed and, in order to make reasonable predictions, would require an excessive amount of computer time. As several authors have concluded, there is no numerical model for complex terrain today that is a good forecasting tool. Table 4 shows the works consulted to reach this opinion.

One developing use of numerical models is the application of simple mass consistent wind models to diagnose wind distributions in complex terrain on the basis of a few observations. Although the validity of such models still awaits testing, their requirement for only small computer resources as well as some promising results from preliminary experiments (see next section) suggests that their application should be pursued.

2.1.4 The Application of AI/Expert Systems to the LLT Forecast Problem

AI is a generic term referring to the use of a computer to imitate human behavior that is generally thought to require intelligence. Expert systems (ES) and knowledge-based systems (KBS) are less stringent terms dealing with the use of computers to emulate human thought processes under stricter guidelines (using empirical relationships based on experience and knowledge of the programmer). Racer and Gaffney (1984) introduced the term interpretive processing (IP) as an application of ES/KBS in meteorological applications and quote the following definitions.

TABLE 4. EXAMPLES OF MESOSCALE NUMERICAL MODELS

Fosberg et al. (1976)	A simple mass consistent wind model.
Dickerson (1978)	Mass consistent wind model specifically for mountainous terrain.
Sherman (1978)	Mass consistent wind model.
Erasmus (1986a)	Multilayer mass consistent model of Oahu under Trade Wind influence.
Yamada (1981)	Complex, 9-level, model of nocturnal drainage flows including a multilevel soil moisture and heat flux model
Yamada (1983)	Description of a simplified turbulence model that is still highly complex relative to a simple diagnostic model.
Meyers et al. (1985)	A Large Eddy Simulation (LES) model. (This is essentially a work-in-progress report.)
Yamada and Kao (1986)	Simulation of the marine boundary layer during GATE, 3-D, 2nd moment, turbulence closure model.
Mellor and Yamada (1974)	Comparison of models for turbulence in the planetary boundary layer.
Wyngaard (1985)	Considers in general terms the value of current modeling efforts and suggests that there may be room for cost-effective improvement.
Wyngaard (1985b)	Describes in general terms LES techniques and suggests where this form of predictive numerical model might prove useful.
Erasmus (1986b)	Evaluation of a diagnostic mass-consistent model against observed data.
Henmi (1988)	Compares a complex multilayer model with a simplified model. Found that the simplified model showed unrealistic windspeeds.

AI is a subfield of computer science concerned with the concepts and methods of symbolic inference by a computer and the symbolic representation of the knowledge to be used in making inferences. A computer can be made to behave in ways that humans recognize as "intelligent" behavior in each other (Feigenbaum and McCorduck, 1983).

AI is the development of computer programs that can solve problems normally thought to require human intelligence (Duda and Shortliffe, 1983).

ESs...[are]...problem-solving computer programs that can reach a level of performance comparable to that of a human expert in some specialized problem domain (Nau, 1983).

...a KBS is an AI program whose performance depends more on the explicit presence of a large body of knowledge than on the possession of ingenious computational procedures; by expert system we mean a KBS whose performance is intended to rival that of human experts (Duda and Shortliffe, 1983).

IP is defined as a computer interactive procedure that enhances the abilities of the weather forecaster to decide on a forecast. The procedure makes it easier to draw conclusions from the meteorological analysis of observational data, forecasting techniques, and past forecaster experience available when deciding on a forecast.

The possible applications of AI to meteorology cover a spectrum, ranging from decision trees, such as developed by Brown (1986) to forecast programs capable of learning (Gaffney and Racer, 1983) and beyond. The National Weather Service (NWS) is increasing its automation of field operations as part of its modernization efforts, with one of its areas of concentration being the field of IP. Since the forecast problem involves reduction of available data, identification of significant data and guidance (numerical and manual), and the application of both explicit and implicit relationships, rules of thumb, etc. to create a forecast product, a competent IP system would be of great benefit. Racer and Gaffney (1984) give an example of a prototype IP, furthermore, they (Racer and Gaffney, 1984) envision a three-fold benefit from the application of KBS/ES to weather forecasting

(1) to provide improved data analysis and decision-making support due to enhanced consistency and thoroughness,

(2) to support training of new forecasters,

(3) to support skill maintenance for experienced forecasters, especially with regard to their actions in infrequently occurring/unfamiliar situations.

Unquestionably, an LLT forecast system that accomplished the above items would go far in alleviating the LLT forecast problem at regional and local forecast offices (for example, see next section).

AI technology is being used in varying degrees as a forecast tool. As noted Brown (1986) has developed a simple decision tree approach to forecasting downslope windstorms in Colorado. His is a program using "if-then" structures to consolidate significant data (both analysis and numerical guidance) into a valid indicator of the probability of strong downslope winds. Gaffney and

Racer (1983) have developed a prototype system for severe storm advisories that is capable of "learning" behavior. This system is based upon formalized rules developed by Crisp (1959) and Miller (1972) of the Air Force GWC. Racer and Gaffney (1986) quote a personal communication with J. T. Schaefer of the National Severe Storms Forecast Center detailing a KBS that includes "a severe weather checklist of 10 parameters that are evaluated as a group using "if then" rules to determine the "possibility" of a storm." Racer and Gaffney (1986) also detail a diagnosis procedure for evaluating numerical guidance materials developed by Simpson (1971) at the NWS National Hurrican Center. It used a decision ladder to systematically analyze the performance of numerical models with the goal of improving them.

There is an apparent-gap in the spectrum of technical applications of AI to weather forecasting. Gaffney and Racer's "learning" program is at the high end, but it is only a prototype. The checklist/decision tree approach (for example, Lee, 1988), at the low end of the spectrum, is the only application of AI commonly in use. While this is an improvement over manual methods, much greater benefits could be realized by the use of "smarter" systems.

Possible candidates would be the refinement of the dependence of a local turbulence index (LTI) (see next section) on wind direction, relative weighting of input parameters, etc. The system would likely use numerical input/output rather than a "natural language" user interface characteristic of full AI systems. The program should include a training mode with blocks for: (1) general forecaster familiarization, (2) training on use of program, and (3) practice cases/case studies.

LLT forecasting/nowcasting would greatly benefit from the application of AI concepts, especially with the greater availability of powerful microcomputers and reasonably priced remote sensing devices. In an effort to solve the LLT prediction problem at Fort Irwin, Lee (1988), has recently developed and tested an interactive LLT forecast aid to be operated in parallel with a local observation network and an objective wind analysis program (Henmi et al., 1988). Results are promising. In the current study (next section), an LLT forecast method based on a modification of one of the indices presented in table 1 is proposed for use with a local data base and an efficient objective analysis technique to determine the local wind field. As will be seen, the proposed technique could be easily adapted for forecaster interaction and continuous nowcast display, two important attributes of a practical AI system.

In addition to the literature review above, a limited search was conducted for data bases that include simultaneous tower and aircraft measurements of LLT. Such data could allow the development of improved statistical forecast techniques of LLT. By far, the most comprehensive LLT/tower data base collected to date was LO-LO CAT (Jones et al., 1970). Data from Project PHOENIX, a more recent data-collecting program, offer promise. It is currently being analyzed by Lilly et al. (1988). National Center for Atmospheric Research (NCAR) maintains many data bases from its Research Aviation Facility (RAF) aircraft investigations, however, those have not been examined closely. Personal communications with interested scientists generally discouraged the search and the attempted utilization of such data bases as expensive, with a good probability of being unproductive. Further investigation is needed.

It is clear from the previous sections that a dramatic improvement in LLT forecasting/nowcasting awaits the wide availability of sophisticated boundary layer measurements as well as realistic mesoscale numerical models that can be operated economically in near real time. Since these improvements are not likely to be seen by the operational forecaster for many years, a practical recommendation is that current methods be used more efficiently. On the basis of the literature review and the Fort Irwin problem discussed below, it is clear that significant improvements in local LLT forecasts/nowcasts can be made by combining the simplest AI approaches (for example, checklist/decision tree) with available forecast/nowcast techniques (table 1) and with current computer, communication, and measurement technology.

2.2 The LLT Problem at Fort Irwin

2.2.1 Background

LLT associated with high winds at the NTC at Fort Irwin, California, occasionally causes aircraft accidents or, more often, the cancellation of missions of helicopters operating in support of training exercises. The latter problem occurs because the helicopters may not fly into areas where severe turbulence is observed or predicted. High winds and turbulence are common during fall and spring and proportionately less missions should be expected to be flown during those periods. However, there is a general perception (no statistics available) among command and flying personnel at NTC that incorrect "overforecasts" of severe LLT contribute significantly to the total number of cancelled missions.

It is the purpose of this portion of the current study to document the Fort Irwin LLT problem and to seek answers to the questions: "Can the LLT forecasts be improved significantly? and if so, how?"

2.2.2 Procedures

The Fort Irwin problem was documented by means of: (1) a review of the NTC Forecaster Handbook (1987), (2) a tour of the Post, (3) interviews with the Science Advisor, local pilots, and forecasters, (4) a review of George Air Force Base forecasting procedures, (5) an examination of a number of past case studies of LLT incidents on or near the Post, and (6) a questionnaire completed by NTC permanent party pilots.

2.2.3 Some Important Characteristics of LLT at Fort Irwin

Fort Irwin occupies an area of about 30 x 30 miles^2 in the Mojave Desert 35 miles northeast of Barstow, just south of Death Valley. It lies about 85 miles to the north of the San Bernardino and San Gabriel Mountains and about the same distance to the east of the southern Sierra Nevada where the highest peaks exceed 10,000 feet mean sea level (m.s.l.). On the Post, the terrain is characterized by rugged peaks separated by broad valleys (figure 2). Elevations (m.s.l.) over the Post vary widely from near 6,100 feet in the northeast corner of 1,300 (feet) in the southeast.

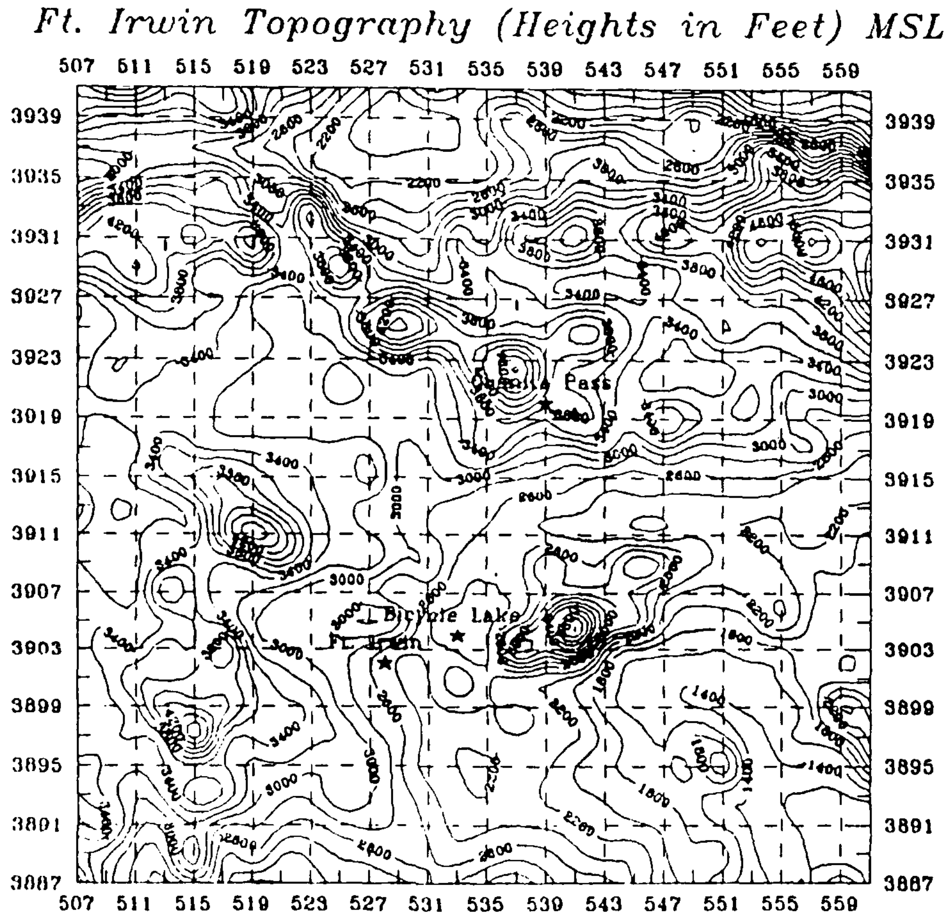


Figure 2. Fort Irwin topography.

LLT that causes the most difficult mission scheduling problems at Fort Irwin during fall and spring is caused mainly by interactions of the rugged terrain with very strong winds that occur during the passage of fronts, and with mountain waves (NTC Forecaster Handbook, 1987). Although significant, convectively produced LLT occurs throughout the year, it does not present a problem as serious as the frontal and mountain-wave generated LLT. This is evidently due to a better forecaster/pilot understanding of convective phenomena. Furthermore, many of the most important characteristics of moist convection are easily identifiable by eye and/or by radar. Also, there is a strong relationship between thermal activity, time of day, and specific terrain features. In contrast, the production of mechanical turbulence is not as well understood by pilot or forecaster; it occurs on smaller time and space scales and is further complicated by the extreme variations in terrain across Fort Irwin. For these reasons, the study of the Fort Irwin LLT problem concentrates on mechanically produced LLT.

2.2.4 Turbulence Cases

Synoptic conditions were examined for cases where aircraft encountered significant turbulence on or near Fort Irwin. Dates of the 13 incidents (furnished by the U.S. Army Atmospheric Sciences Laboratory (ASL)) are listed in table

5. Although other cases were available (Lee, 1988), they are not considered here because either the dates fell outside the October-May period (two cases) or there was insufficient information (three cases). The analysis of the remaining cases included the documentation of synoptic patterns (location of fronts, troughs, examination of wind, contour, pressure, and pressure tendency gradients, etc.). Unfortunately, more detailed analysis was only possible for two cases because the turbulence incidents were poorly documented, that is, the location and time and, in some instances, the date could not be verified. These uncertainties, coupled with the already sparse distribution of surface and radiosonde stations in the area, prohibited further systematic analysis.

TABLE 5. DATES OF SIGNIFICANT LLT INCIDENTS*

18 Apr 76	25 Nov 86
14 Apr 83	6 Jan 87
16 Jan 84	16 Jan 87
7 Nov 84	5 Feb 87
27 Mar 85	5 Mar 87
7 Oct 85	19 Apr 87
6 Mar 86	

*furnished by ASL

The primary result of the case study macroanalysis was that 9 of the 13 cases occurred in the vicinity of surface fronts; one was associated with a sharp upper level trough (no clear surface front); and one was related to a surface high-pressure system located over the Great Basin. These conditions agree with what is known generally about LLT turbulence-producing processes at Fort Irwin (NTC Forcaster Handbook, 1987); strong surface winds (and therefore LLT) are caused either by mountain waves or by strong pressure gradients in the vicinity of cold fronts. Furthermore, these features are identifiable in the large-scale synoptic pattern and should therefore be anticipated by trained forecasters using standard analysis/"met-watch" procedures.

2.2.5 Pilot Questionnaires

As noted in the literature review and verified above, synoptic patterns are good indicators of the probability of LLT occurrence over a broad area. However, the documentation of details of the distribution of LLT over an area of the size of Fort Irwin clearly requires subsynoptic scale information. The fulfillment of this requirement is difficult because historical weather data (pressure, temperature, winds, etc.) for the Post are primarily limited to a single location, the Bicycle Lake Army Airfield (BYS). Furthermore, aside from the poorly documented cases listed in table 5, data on turbulence occurrences around the Post are nonexistent.

In order to overcome this problem, at least partially, a questionnaire related to LLT was developed and distributed to Fort Irwin permanent party helicopter pilots. That group was selected (for example, as opposed to rotation pilots) because of their interest in the problem, knowledge of the Post, and similar and extensive flying experience. The 14 pilots who responded to the questionnaire had an average accumulated flying time of 1946 hours, with an average of 847 hours at Fort Irwin.

The questionnaire instructed the pilots to describe LLT not associated with thunderstorms. They were also asked to characterize typical missions, to document sources of meteorological information, to evaluate forecasts, and to give suggestions for forecast improvement. A sample questionnaire is given in appendix A; a summary of all responses except those related to the spatial distribution of LLT are contained in appendix B. The responses to the LLT distribution questions are described briefly below and presented in detail in appendix C.

Figure 3 summarizes the major result of the questionnaire, that is, an estimate of the location of the primary LLT problem areas on the Post. It is a composite of individual maps prepared by the pilots in response to the instruction: "on the attached map, circle those locations which have the highest frequency of turbulence significant to your operations." The association of those areas with particular topographical features is noted. Many of the pilots who responded to the questionnaire provided detailed comments about specific turbulent areas (numbered areas in figure 3). The comments are given in appendix C. These should prove useful in the future for both pilot and forecaster training. Although the utility of such information is clear, caution is advised. The sample is small and the pilot's reports are biased towards the primary operational areas; thus the map is simply a guide and does not represent a "climatology" of any sort.

2.2.6 Causes of the LLT Forecast Problem at NTC

On the basis of the site visit and the questionnaires described above, it is clear that the primary cause of the LLT problem at Fort Irwin originates with the production of a point forecast for NTC by the weather detachment at George Air Force Base (which carries the primary responsibility for local LLT forecasts for Fort Irwin). Despite the fact that part of the Post will often have severe turbulence conditions as predicted. Fort Irwin personnel will perceive such forecasts as erroneous "overforecasts" because a gradient in turbulence intensity exists across the Post, that is, a significant portion of NTC is still "flyable" although the entire Post is closed.

The problem, therefore, is not always one of inaccurate forecasts, but rather that the user's needs have exceeded the forecaster's current capabilities.

The perception of "bad" forecasts has damaged forecaster credibility and has led to forecast "shopping" by pilots and the necessity for command personnel to override forecasts in order to accomplish missions.

Another unfortunate ramification of the perceived problem is that rotation forecasters at Bicycle Lake (many of whom are not familiar with NTC forecasting problems) do not benefit greatly from their NTC experience. They are often left out of the forecast loop, relegated to observer or briefer status, and ignored by both pilots and command personnel. Based on our perception, they are essentially an under-utilized resource.

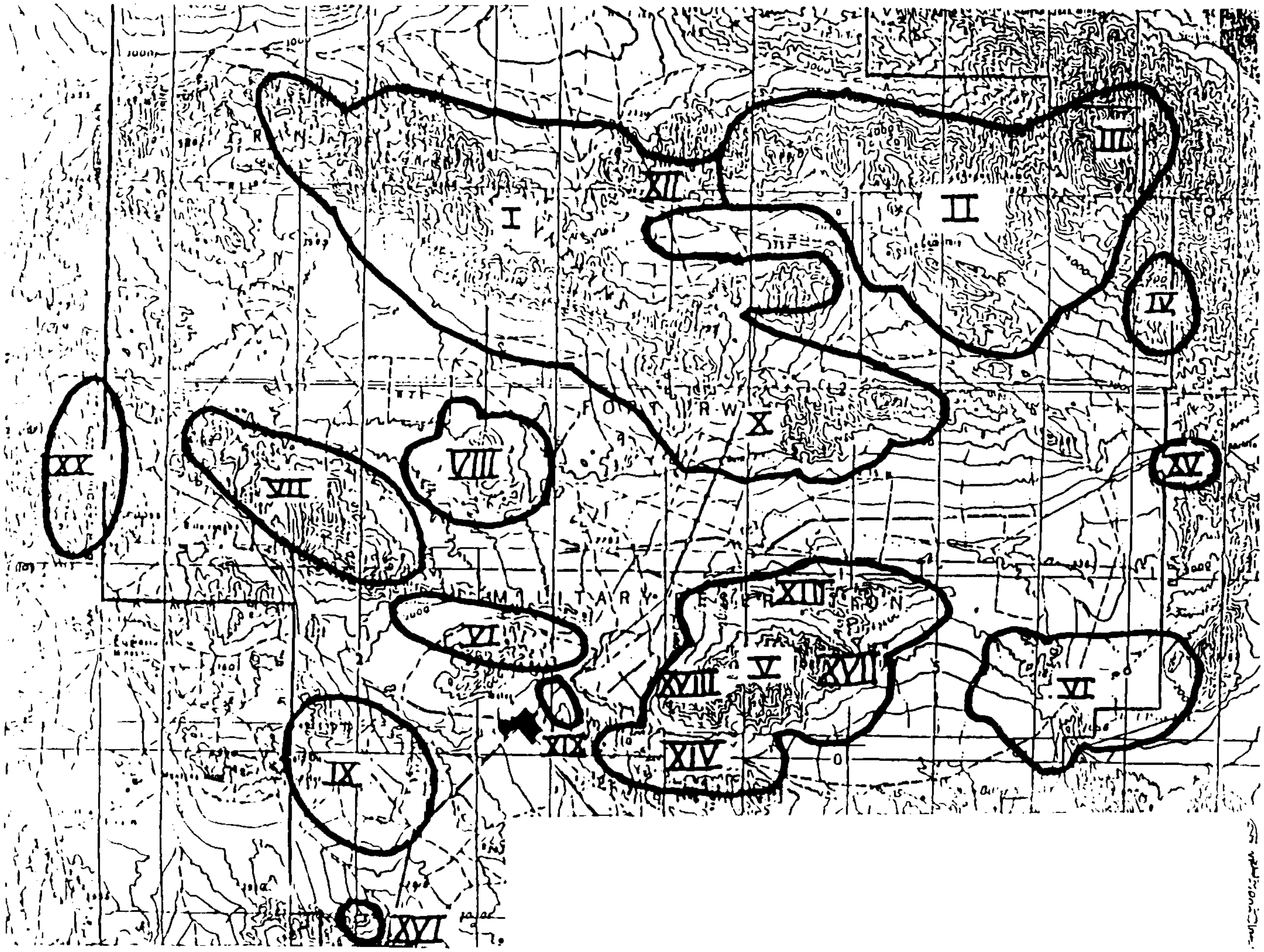


Figure 3. Map of Fort Irwin turbulence areas based on pilot questionnaires.

Although the forecast methods used by VCV to produce LLT predictions for Fort Irwin reflect currently accepted methods used by the Air Weather Service (for example, AWSP 105-56, 1986) and other agencies, their gross detail cannot solve the Fort Irwin problem. In order to solve the problem described above, a new forecast system is needed, that is, one that recognizes the scale of the turbulence and the required detail of the forecasts.

A minimal but practical LLT forecast/nowcast system would include (1) a mesoscale network of surface observation stations across the Post with data accessible in real time, (2) a system of regular pilot reports of turbulence intensity over the Post, and (3) an objective analysis (nowcasting) and forecast system based on both large and local scale information. The surface observation stations, coupled with local LLT reports would provide the data base for the development and continued improvement of objective nowcast/forecast techniques.

In addition to the three items listed above, there is an important fourth component for a successful system...(4) the human factor. As was clearly noted in the literature review, successful forecasting over small space and time scales requires "met-watching," that is, it is a labor-intensive task. The rotation forecaster at Fort Irwin, given the proper techniques and training, can certainly bear a significant part of the LLT forecast responsibility. The only drawback foreseen will be maintaining continuity from rotation to rotation.

Assuming that items (1), (2), and (4), above, will be available, the next section discusses the development of a potential method for the objective analysis (nowcasting) and forecasting system for Fort Irwin.

2.2.7 An LLT Index-Based Forecast Scheme

A useful objective forecast scheme for LLT must evaluate the contributions of all significant physical processes that cause the turbulence. It must be practical, that is, easy to learn, easy to use, and based on available data bases. As discussed in the literature review, the BTI has been used as a major input to worldwide LLT predictions by GWC of the U.S. Air Force during the mid-sixties and early seventies (Burton, 1964; Burnett, 1970). It was a successful objective technique (for example, Jones et al., 1970), generally satisfying the requirements stated above and specifically addressing terrain roughness. In the following, BTI is described in detail, a modification is proposed to adapt it to an area the size of Fort Irwin, and, finally, an example of its use is demonstrated for a case of severe LLT.

The BTI (for example, Burnett, 1970) is given by

$$BTI = R + V + S + T \quad , \qquad (1)$$

where R is "roughness," the difference between the highest and lowest terrain features in the area of interest in hundreds of feet. V is windspeed, at 2000 feet above ground level (AGL) in knots. S is "stability," the lapse rate

(10 x DEG C/1000 feet) in the lowest 100 millibars. T is "synoptic forcing" absolute value of the 3-hour pressure tendency in tenths of a millibar.

Threshold values of BTI for various turbulence intensities and category 1 aircraft are given in table 6.

TABLE 6. BTI AS A FUNCTION OF TURBULENCE LEVEL

Light	60	Moderate-Severe	90	Severe	100
Moderate	70			Extreme	120

BTI has been successfully applied to large areas (for example, the Mojave Desert), however, an adaptation to an area of the size of NTC causes several difficulties. Although the values of wind, stability, and pressure tendency may be similar for the smaller area, the numerical value of the roughness component will usually be less than its value for a larger area. It follows that total BTI values will also be smaller with roughness being weighted less for the smaller area. Thus, threshold BTI values for critical LLT will be lower than those defined by past experience (table 2). Another problem that arises is that observations of winds, stability, and pressure tendency observations are not usually available on the same scale as the terrain information. In order to deal with these problems, the BTI computation has been modified in the following manner. First, it is assumed that the stability (S) and pressure tendency T primarily reflect large-scale influences, and may be represented by rather gross measurements, for example, a single sounding and one representative pressure tendency for all scales of importance. Locally, however, roughness (R) and windspeed (V) may differ widely from their macroscale values.

The modified index computation is then performed in two steps. Initially a macroscale BTI (Eq. (1)) is defined for the broad area encompassing Fort Irwin. That index is then modified for local measurements of roughness and wind to yield a "Local scale Turbulence Index," that is,

$$LTI_i = BTI \times (R_i + V_i)/(R + V)_x \quad , \tag{2}$$

where BTI is given by Eq. (1), suscript i represents one of several measurement points or gridpoints, and subscript x indicates the maximum measured gridpoint value. In order to maximize LTI, in the case that the denominator of Eq. (2) exceeds BTI, then

$$LTIi = (R + V)_i \quad . \tag{3}$$

2.2.8 The Application of LTI

The LTI computation was tested to determine whether clear gradients of the index would develop across the Post under large-scale conditions, which are diagnosed as turbulence as indicated by BTI. Since no good data base is available, computations were made with data from a known case of significant LLT. The case chosen was the 27 March 1985 incident involving the crash of an O-2 at Fort Irwin during mountain wave/LLT conditions.

Since the distribution of winds was not available, surface (10 m) winds were interpolated at 2 kilometer grid points by means of COMPLEX adapted to the Fort Irwin terrain. Input consisted of terrain data at the grid points and a simple wind profile based on surface and 850 millibar data estimated for BYS.

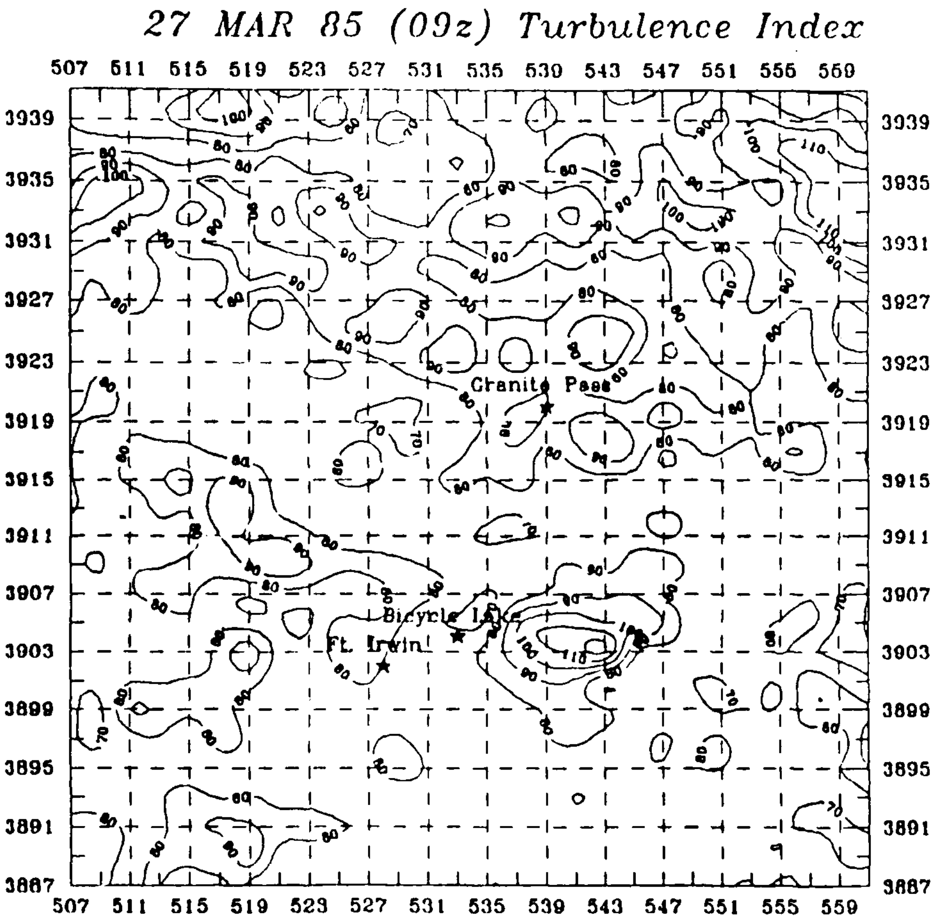
For the computation of BTI, macroscale roughness was determined as a maximum terrain height difference across the Post. For LTI, "local" roughness at grid points was estimated from topographical charts as the maximum difference in terrain height surrounding each grid point. The 3-hourly pressure tendency was determined as an interpolated value from surrounding weather stations, large-scale stability was computed from the estimated surface to 850 millibar lapse rate at BYS, and the macroscale for BTI was estimated from 850 millibar at BYS.

Since the purpose of the experiment was to determine whether clear LTI gradients would develop under realistic macroscale conditions, the boundary layer structure of COMPLEX was arbitrarily set to produce a maximum response in surface winds with the given wind profile. Calculations of LTI were made for the time of the turbulence incident (1500Z) and 6 hours before and after.

The LTI analyses are presented in figures 4, 5, and 6 for each time period.* Despite the high values of BTI (also see table 2). LTI varies widely across the Post in each case. As would be expected, there is a strong spatial correlation with terrain features (compare with figure 2) indicating a strong contribution by local roughness. If these are realistic, they suggest that LTI may offer help to the forecaster for the discrimination between "flyable" and "unflyable" areas across the Post on occasions when the macroscale forecast would close the entire area to flying.

The inspection of LTI analyses in figures 4, 5, and 6 emphasizes other potential advantages of the index. For example, it is easy to interpret objectively by both forecasters and pilots, lending itself to a simple display (for example, on a monitor). COMPLEX and similar objective wind analysis schemes run quickly on available microcomputers and thus such analyses and the index could be updated in nearly real time and displayed continuously. Furthermore, predicted values of BTI from large-scale forecasts could be updated locally with local values of V and R.

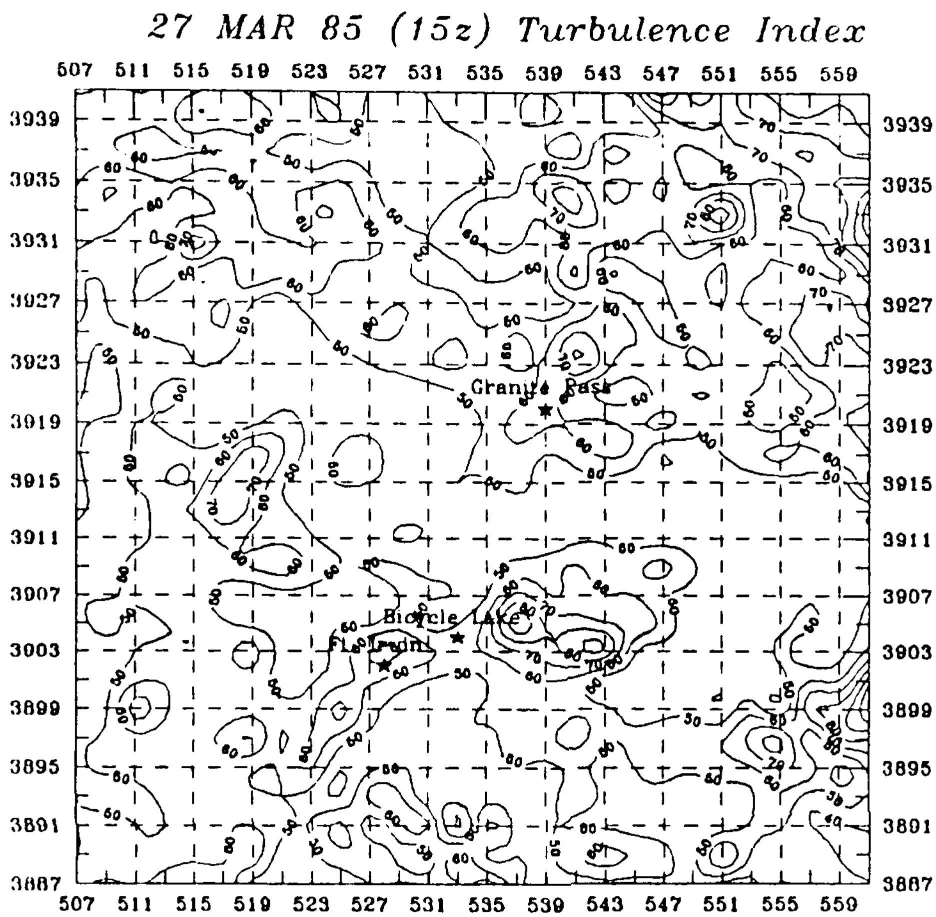
*Analyses of COMPLEX windspeed and wind direction for each time are presented in appendix D.



LTI range 66 - 123

BTI	= 131
SFC wind	= 260/30
850mb wind	= 290/35
Lapse Rate	= 3.0°/1000ft
App	= -20
BL Thickness	= 1100m

Figure 4. LTI for 0900Z.



LTI range 28 - 111

BTI	= 111
SFC wind	= 230/20
850mb wind	= 270/35
Lapse Rate	= 3.0°/1000ft
App	= 0
BL Thickness	= 700m

Figure 5. LTI for 1500Z.

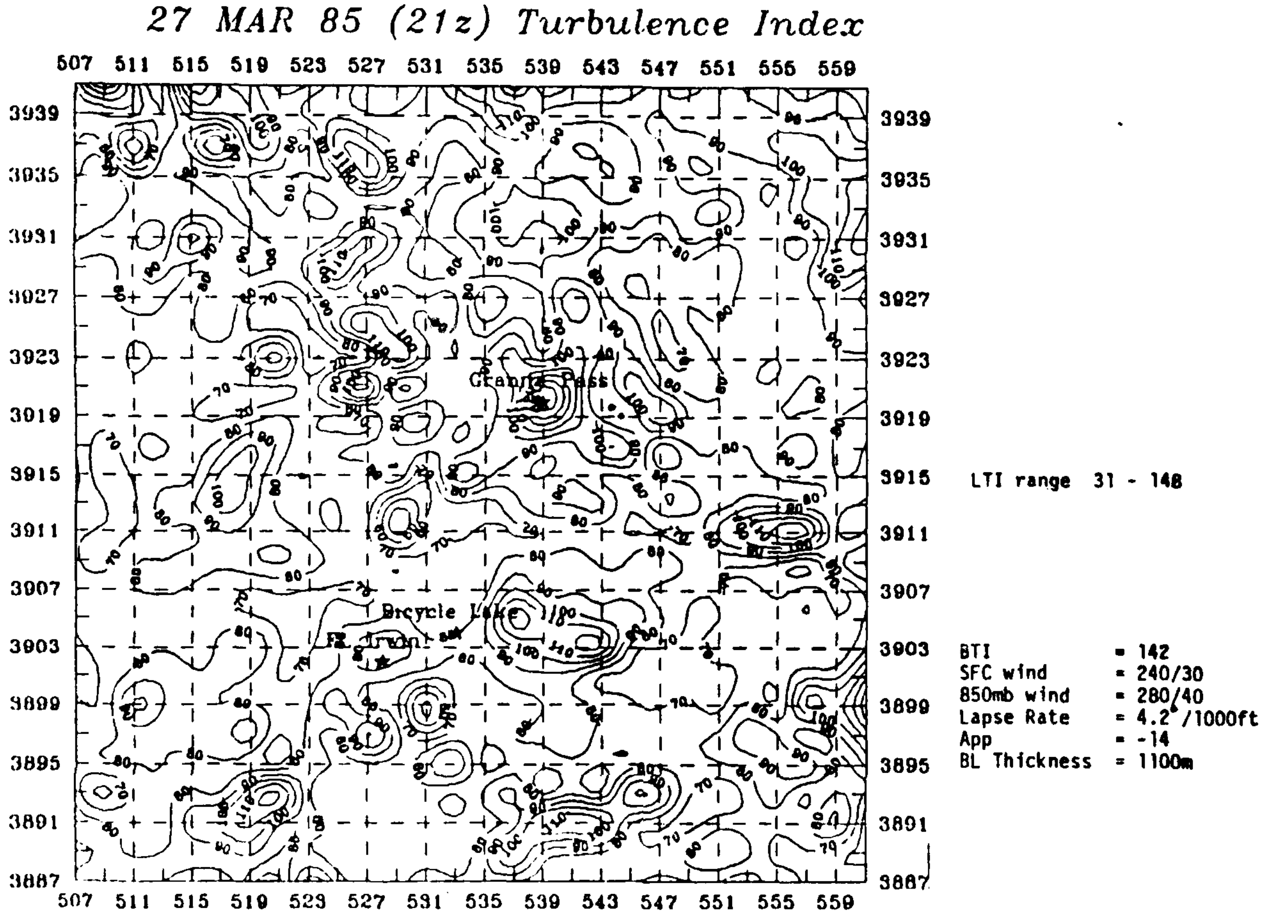


Figure 6. LTI for 2100Z.

The major shortcoming of the LTI computation presented here is that detailed local wind observations are nonexistent. The validity of the scheme described here depends strongly on the availability of wind observations and on the accuracy of the wind interpolation scheme. It should be pointed out that the computation of low-level turbulence index (LLTI) at the site of the wind observations is not dependent on the interpolation algorithm. The success of COMPLEX interpolations, on the other hand, is strongly dependent on knowledge of the shape of the top of the boundary layer. Furthermore, COMPLEX does not explicitly deal with nonhydrostatic phenomena that are often characteristic of strong wind regimes in rugged terrain. Several other questions await a suitable turbulence and surface data base. These include the following: (1) what is the smallest horizontal scale on which LTI can be calculated and still be meaningful? (2 kilometers were selected arbitrarily in the present case); (2) what is the relative importance of each variable (R, S, T, V) as the scale decreases? (3) what is the possibility of modifying LLTI as a function of wind direction to take into account lee waves and other wake phenomena? (4) would an interpolated wind at a higher level be more appropriate for LTI computation than a 10-meter wind?

2.2.9 Development of an Expanded Data Base

The previous sections have demonstrated that significant improvement of LLT forecasts at Fort Irwin will require a data base consisting of surface observations and turbulence observations on the scale of the desired forecasts. The literature review has revealed that data bases of the desired quality are rare, in general, and nonexistent for Fort Irwin, specifically. Current plans to place a number of automated remote weather stations around the Post, coupled with the success with the pilot questionnaire discussed earlier, suggest that the establishment of a program to regularly acquire and archive pilot report (PIREPS) could provide such a data base. In the short run, such a program would open up forecaster/pilot communication channels on a more regular basis. In the long run, the data base would provide information for the systematic development of improved LLT nowcast/forecast methods on a small-scale desired by pilots and command personnel.

Towards this end, an efficient pilot report form was developed and distributed to Fort Irwin pilots. A sample of the form is presented in appendix E. Data are currently being archived at ASL, White Sands Missile Range, New Mexico.

3. SUMMARY OF RESULTS, CONCLUSIONS, AND RECOMMENDATIONS

The literature review has revealed that current LLT forecast techniques are a result of the need to forecast a small-scale phenomenon with large-scale data. Thus aside from occasional PIREPs, the forecast techniques lean heavily on large-scale pattern recognition and evaluation of those patterns with available large-scale data. Although the current forecast techniques lend themselves to automation and objectivity at the weather central, at the local level, a large amount of subjectivity is introduced as a function of the local forecasters experience. Furthermore, by the very nature of LLT, its accurate prediction is labor intensive at the local level, and the manpower is not always present, especially in critical situations.

The literature also indicated that improvements in LLT in the near future would most likely come from the improvement of local data acquisition and objective analysis and display, that is, utilizing current instrument communications and microcomputer technology.

The LLT problem at Fort Irwin is a good example of the problem with current LLT forecasting. Although standard LLT forecast methods are used and there is no evidence that the resulting accuracy is not what should be expected, the perception of the forecast users is that the forecasts are inaccurate. The reason for this perception, is that the users' needs simply exceed the current forecast capabilities.

A survey of the turbulence problem was completed primarily as a forecast aid. A prototype objective forecast scheme was then developed to eliminate variations in forecast quality while capturing the smaller scale details of the turbulence field as required by NTC operations. Finally, a local PIREP form was developed to increase forecaster knowledge of the problem and to provide a data base for the development of better forecasts.

The literature review was not comprehensive. For example, further investigation of the results of Atmospheric Studies in Complex Terrain (ASCOT) and the Alpine experiment (ALPEX) should be conducted to determine applications to LLT. Also, there remains a serious need to develop techniques to diagnose and forecast the presence of significant low-level wind shear in elevated inversions, especially in complex terrain. Further work also needs to be done on the development and validation of BTI for LLT. The current data gathering at Fort Irwin offers a unique data base for this purpose, and its analysis should be pursued.

APPENDIX A. PILOT QUESTIONNAIRE

Pilot Questionnaire

1. Pilot Experience

    Name

    Rank

    Career flying time (hours)

    Flying time at Ft. Irwin (hours)

    Flying time in current aircraft type(s)

2. Helicopter Operating Limitations

    List current aircraft type(s) and their operating limitation with respect to turbulence, surface wind conditions, and visibility.

3. Typical Mission

    If possible, characterize a "typical mission:"

    a) Base of operations

    b) Most common take off time(s)

    c) Are there any times of day or night when you never fly?

    d) Most of your flights occur below what altitude (indicate ASL or AGL)?

    e) What is the length of most of your missions (hours and tenths)?

    f) In what area(s) of Ft. Irwin are most of your missions flown?

4. Characteristics of Turbulence Not Associated With Thunderstorms

We are concerned with Low Level Turbulence NOT associated with thunderstorms. With that in mind, please answer the following questions:

Fill out the table below with respect to Ft. Irwin

Low Level Turbulence	Time of Day	Season	General Weather Pattern
Worst Problem			
Least Problem			

5. Low Level Turbulence Areas

On the attached map, circle those locations which have the highest frequency of turbulence significant to your operations. Clearly number each location you have circle on the map and list that number below, giving a brief description of the turbulence problem including the wind direction when the turbulence problem occurs.

6. Turbulence Incidents

List below the dates, times, and locations of any particularly notable turbulence incidents or accidents at Ft. Irwin. If necessary, circle the location on the attached map and label clearly with a number fro cross referencing. Give as many details as possible.

7. LLT Forecasting Accuracy

Comment on the following specific aspects of low level turbulence forecasts for Ft. Irwin.

Accuracy of turbulence intensity forecasts (adequate, over-, or under-forecast?)

Accuracy of forecasts of location, areal extent of turbulence (over-, or under-forecast?)

8. Preflight Briefings

Where do you get your preflight briefings? When do you get them (relative to take off time)?

9. Inflight Advisories

Do you ever receive inflight weather (turbulence) advisories? If yes, from where?

Do you ever give PIREPS? If yes, to whom?

10. Postflight Debriefings

Do you ever give post flight weather debriefings? If yes, to whom?

11. Recommendations to improve LLT forecasts

What are your recommendations to improve low level turbulence forecasts for your operations at Ft. Irwin?

APPENDIX B. SUMMARY OF PILOT QUESTIONNAIRES

Summary of Pilot Questionnaires

In order to better define the LLT problem at Ft. Irwin, a questionnaire was distributed to the permanent party helicopter pilots at the site visit to Ft. Irwin in October, 1987. Fourteen questionnaires were returned by Ft. Irwin Pilots and are summarized below.

1. Pilot experience (13 responses)

	Mean	Median	Range
Career flying time (hrs)	1946	1500	800-5400
Flying time at Ft. Irwin (hrs)	847	700	300-1880
Flying time in type(s)			
UH-1H (12 responses)	1720	700	500-5400
Other	insufficient responses		

2. Helicopter operating limitations

Surface wind conditions ("to crank"):

Maximum Wind	30 knots (35 knots for OH-58?)
Maximum Gust Spread	15 knots

Turbulence:

May not fly into region of reported or predicted severe turbulence (exception: waiver by Post Commander)

Flight not recommended into areas where moderate turbulence has been reported by Category 2 or higher aircraft.

Ceiling/Visibility: Restrictions in uncontrolled mountainous terrain, Day: 0.5 mi/500 ft; night: 1.0 mi/1000 ft.

3. "Typical Mission" (# responses)

a) Base of Operations: Barstow/Dagget (9); Field Site, BYS (4)

b) Most common take-off times: 0300-0700L (13)

c) Times of day or night when flight is restricted None (8); Night (5)

d) Most flights conducted below: 1000 ft (1); 500 ft (1); 300 ft (7); 200 ft (3); 100 ft (2)

e) Mission duration: Mean (9): 3.1 hrs; Duty day (6): 12 + hrs

f) Area(s) of most missions: Entire Post (9); Central and Southern Corridors (3); South (1); BYS (1)

4. Characteristics of LLT and <u>not</u> associated with thunderstorms.

	Time of Day	Season	Weather Pattern
Worst problem	Noon-evening (12) Morning (4)	Summer (3) Fall/Spring (8) Winter (1) all (2)	Near front (2) Strong (SW) winds (5) Other (3)
Least problem	Morning (7) Night (2) Other (2)	Winter (4) Fall/Spring (2) Summer (2) All (3)	Light winds (3) Other (3)

5. See Appendix C

6. See Appendix C

7. Comments on Accuracy of LLT forecasts for Ft. Irwin

<u>Intensity</u>
Fcsts of LLT intensity too strong (6); fcsts ok but tending to be too strong (2); fcsts ok but tending to be too weak (1). Three respondents simply indicated that LLT intensity fcsts were inaccurate.

<u>Area</u>
Fcsts of LLT area too large (9); fcst area ok (1); area too small (2); three respondents simply indicated that fcst areas were inaccurate.

8. <u>Preflight</u> briefings are obtained within 1-1.5 hrs of takeoff from one of the following sources: DAG FSS, VCV, BYS.

9. Inflight advisories are obtained from BYS (8); DAG FSS (2); other acft (1); never (4). Two responses indicated that BYS is not accessible from the air for such information. One respondent stated that BYS does not pass on inflight advisories.

All 14 pilots indicated that they gave PIREPS at one time or another to BYS (12), to other acft (1), and to DAG FSS (3). Although not stated, the conflict between these numbers and those in the paragraph above indicate that some of these PIREPS are not given in flight, but are given after the acft have landed.

10. Postflight weather debriefing have been given at various times by nine (9) of the respondents to BYS (4), Unit Operations (4), DAG FSS (2), VCV (1). Five (5) respondents never give post flight debriefings.

11. Recommendations to improve low level LLT forecasts at Ft. Irwin:

a) Permanent party forecaster at Ft. Irwin (10)
b) Install remote surface wind sensors (9)
c) More PIREPS (2)
d) Other: Better communications, turbulence recovery route to Barstow/Daggett, permanent party observer

APPENDIX C. RESPONSES TO PILOT QUESTIONNAIRE

Responses to Pilot Questionnaire on Low Level Turbulence Distribution at Ft. Irwin (Questionnaire Items #5 and #6)

5. Low Level Turbulence Areas (non-convective)

On the attached map, circle those locations which have the highest frequency of turbulence significant to your operations. Clearly number each location you have circled on the map and list that number below giving a brief description of the turbulence problem, including wind direction when the turbulence problem occurs.

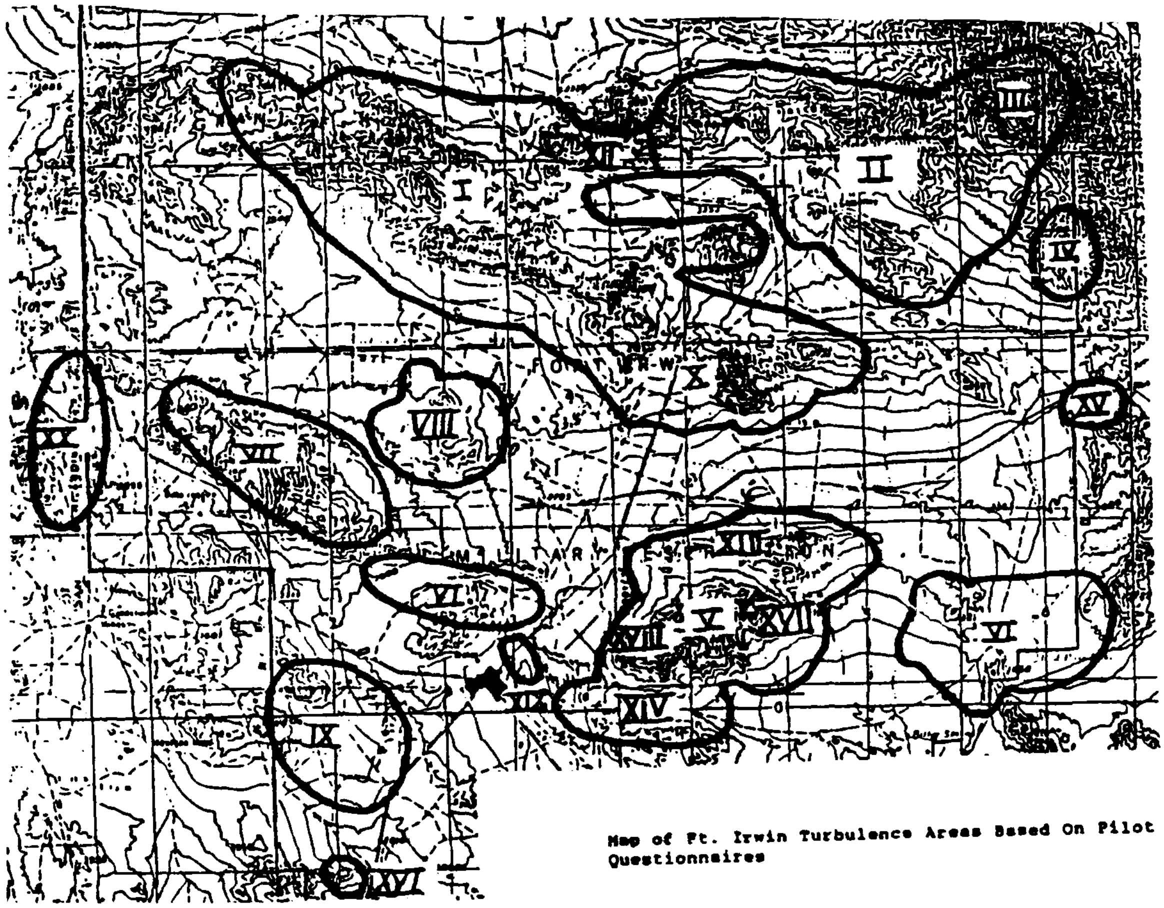
6. Turbulence Incidents (non-convective)

List below the dates, times, and locations of any particularly notable turbulence incidents or accidents at Ft. Irwin. Give as many details as possible.

RESULTS

5. The map on the following page is a composite of those locations which have the highest frequency of turbulence significant to helicopter operations at Ft. Irwin (based on 11 responses). The Roman Numerals on the map correspond with descriptions of the turbulence in the respective areas described in Table 1. The most frequently listed areas were Tiefort Mountain (8), Granite Pass (9), and the area just East of Drinkwater Lake (7).

6. None of the respondents gave complete descriptions (e.g., including dates, times, and locations) of any particularly notable turbulence incidents or accidents at Ft. Irwin. Some partial descriptions are listed in Table C1.



Map of Ft. Irwin Turbulence Areas Based On Pilot Questionnaires

TABLE C1

I	GRANITE MTNS -	1.	Wind from SW 10 knots or greater
		2.	Strong up and down drafts
		3.	Ridge wave
II	BUNKER -	1.	Wind W to SW below 200 ft. AGL
		2.	East of Drinkwater Lake
		3.	Winds from West about 40 knots
		4.	Air flow thru valley (Westerly) can cause strong winds and turbulence
		5.	Winds W to NW severe
III	AVAWATZ MTNS -	1.	Pinacle approaches wind - South
		2.	Wind changes direction up to 30° wind out of S/SW Oct. 1982 during downward portion of an approach to a 6000' pinnacle the UH-1 was caught in a severe downdraft, then updraft causing shoulder harness to lock est. wind velocity 20-30 knots
IV	ENASITE -	1.	Wind from West, wind shifts 30°

TABLE C1
(Continued)

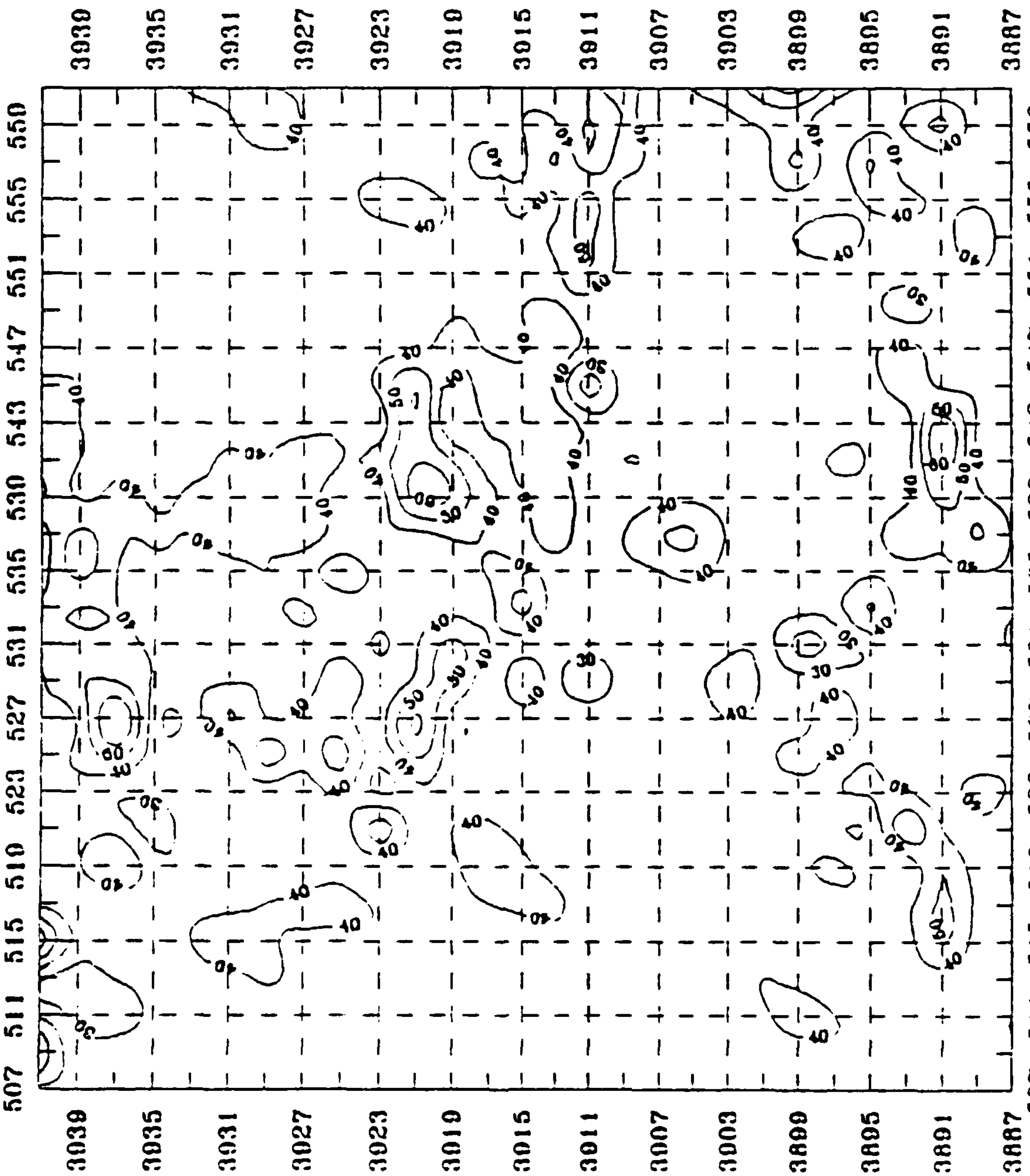
V	**TIEFORT MTNS -**	1.	Sudden tailwind gusts. Wind up to 100° difference between landing zones.
		2.	MTN wave
		3.	Strong updrafts and downdrafts - occurs when the wind picks up
VI	**COYOTE CANYON -**	1.	Heavy turbulence when elsewhere calm. Winds from West
		2.	Has moderate turbulence at times of weather warnings
VII	**SOUTHWALL -**	1.	Winds tend to come from the rear of hovering helicopters. Downdraft
VIII	**CHINAMAN'S HAT -**	1.	Swirling winds
		2.	Wind out of S/SW Sept. 1986, AUH -1, Fully loaded encountered light to moderate turbulence while in slow flight through saddle. The aircraft was in a 20-30 knot tailwind condition - causing power applications resulting in momentary loss of rotor RPA.
IX	**TRAINING AREA B -**	1.	Winds tend to be stronger here than other parts of the Post.
X	**GRANITE PASS -**	1.	Turbulence, wind gusts
		2.	Pass turbulence
		3.	Moderate turbulence at time of weather warnings
		4.	Saddle causes venturi effect
		5.	Winds W to NW severe
		6.	Moderate to severe short duration surface winds from the North
XI	**RED PASS -**	1.	Turbulence and wind gusts make flying difficult
XII	**LEACH LAKE PASS -**	1.	Tailwind, gusts, downdrafts
		2.	Winds out of SW Feb - Mar 87 during straight and level flight along ridge lines, the OH55 aircraft encountered moderate turbulences. Est wind velocity
XII	**SOUTHWALL -**	1.	Wind tends to come from the rear of hovering helicopters downdrafts
XIV		1.	During sustained high wind conditions, is subject to turbulence due to the Venturi effect.
XV	**EAST GATE -**	1.	Winds W to NW severe
XVI	**CHECK POINT -**	1.	Winds W to NW severe
XVII	**HIDDEN VALLEY -**	1.	Winds W to NW severe
XVIII	**BIKE LAKE -**	1.	Winds W to NW severe
XIX		1.	Ridge Winds
XX		1.	During sustained high wind conditions, is subject to turbulence

APPENDIX D. COMPLEX WINDSPEEDS AND DIRECTIONS FOR 21 MAR 85

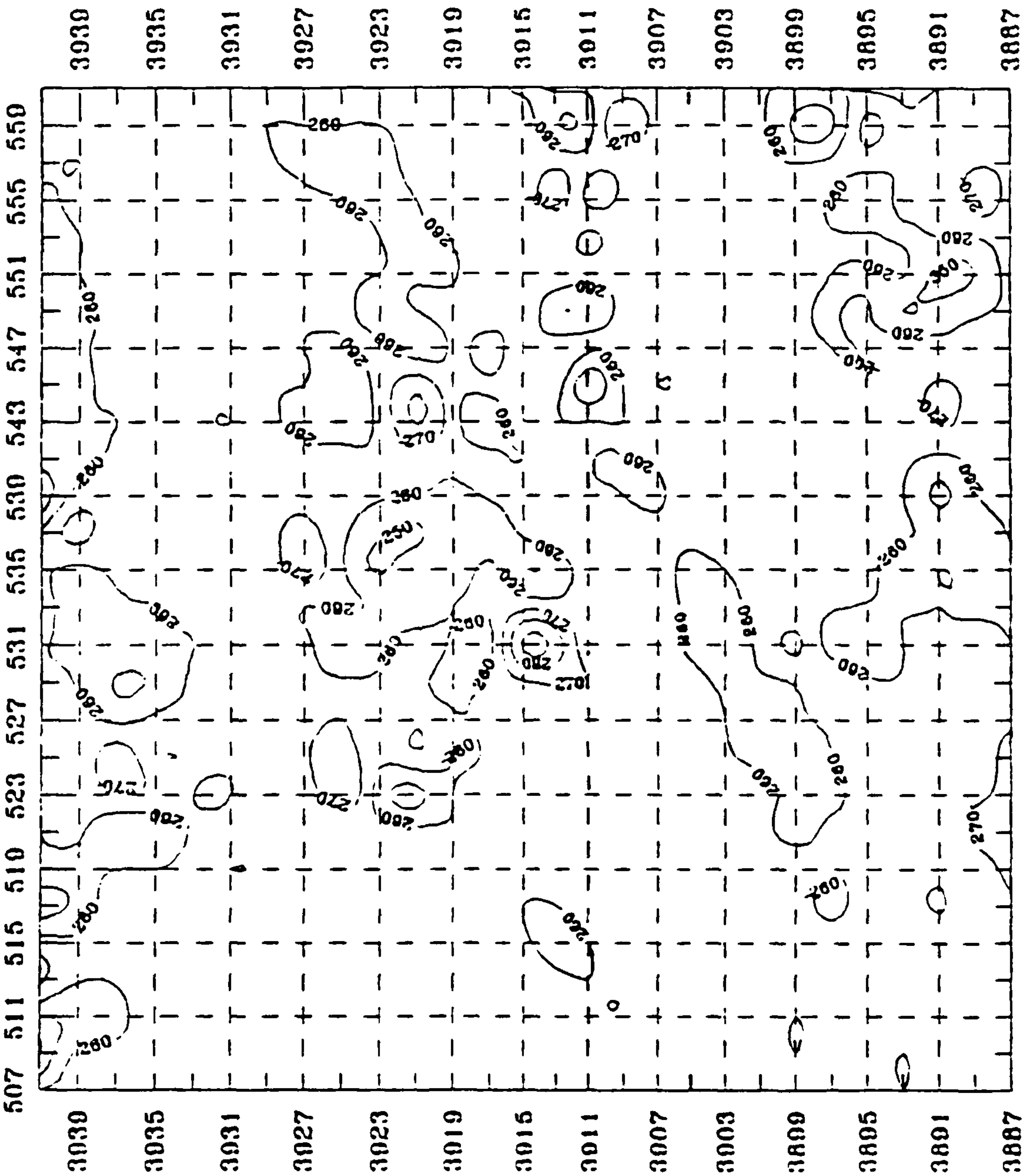
COMPLEX Windspeeds and Directions for

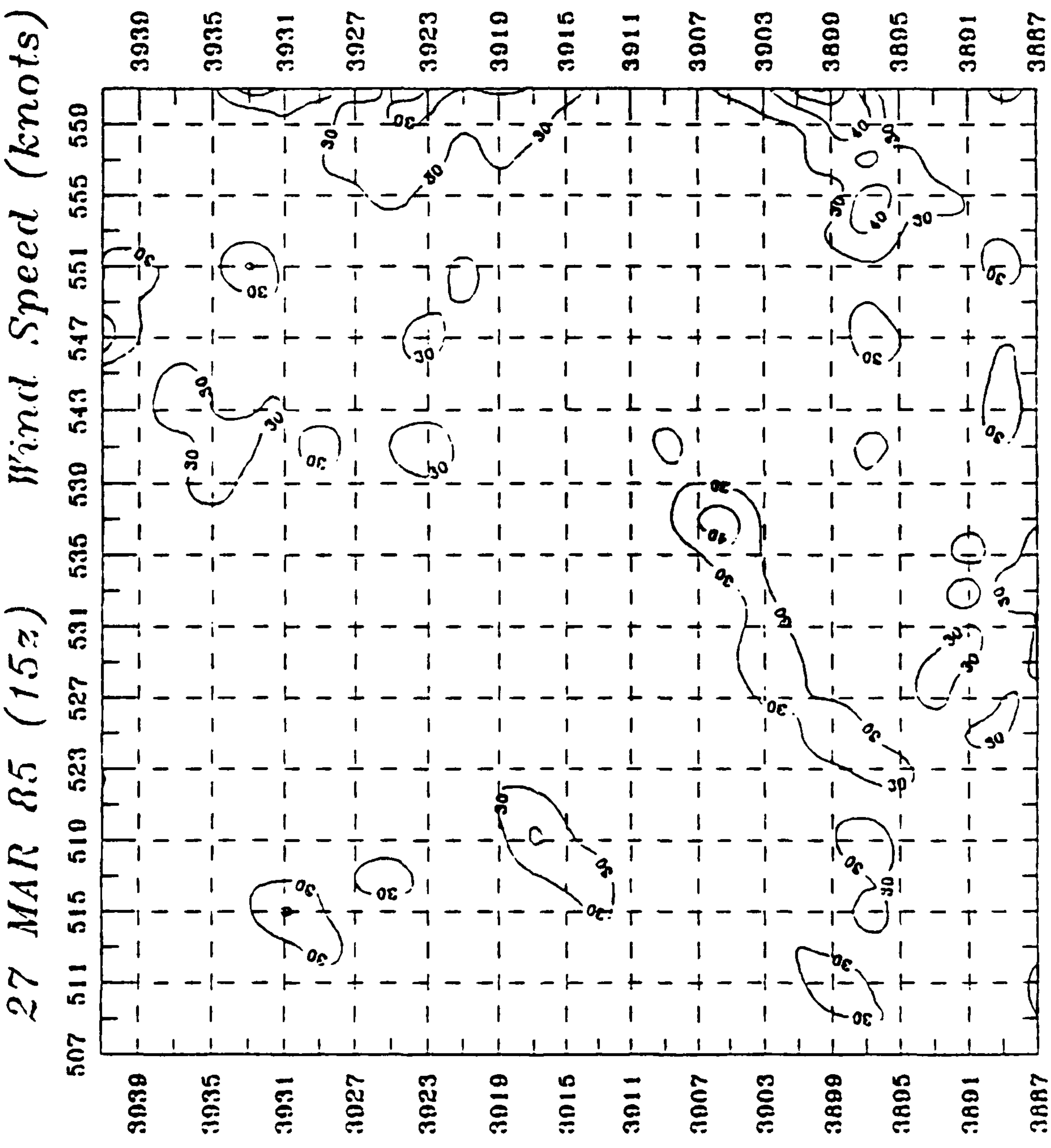
21 Mar 85 at 0900Z, 1500Z and 2100Z

27 MAR 85 (09z) Wind Speed (knots)

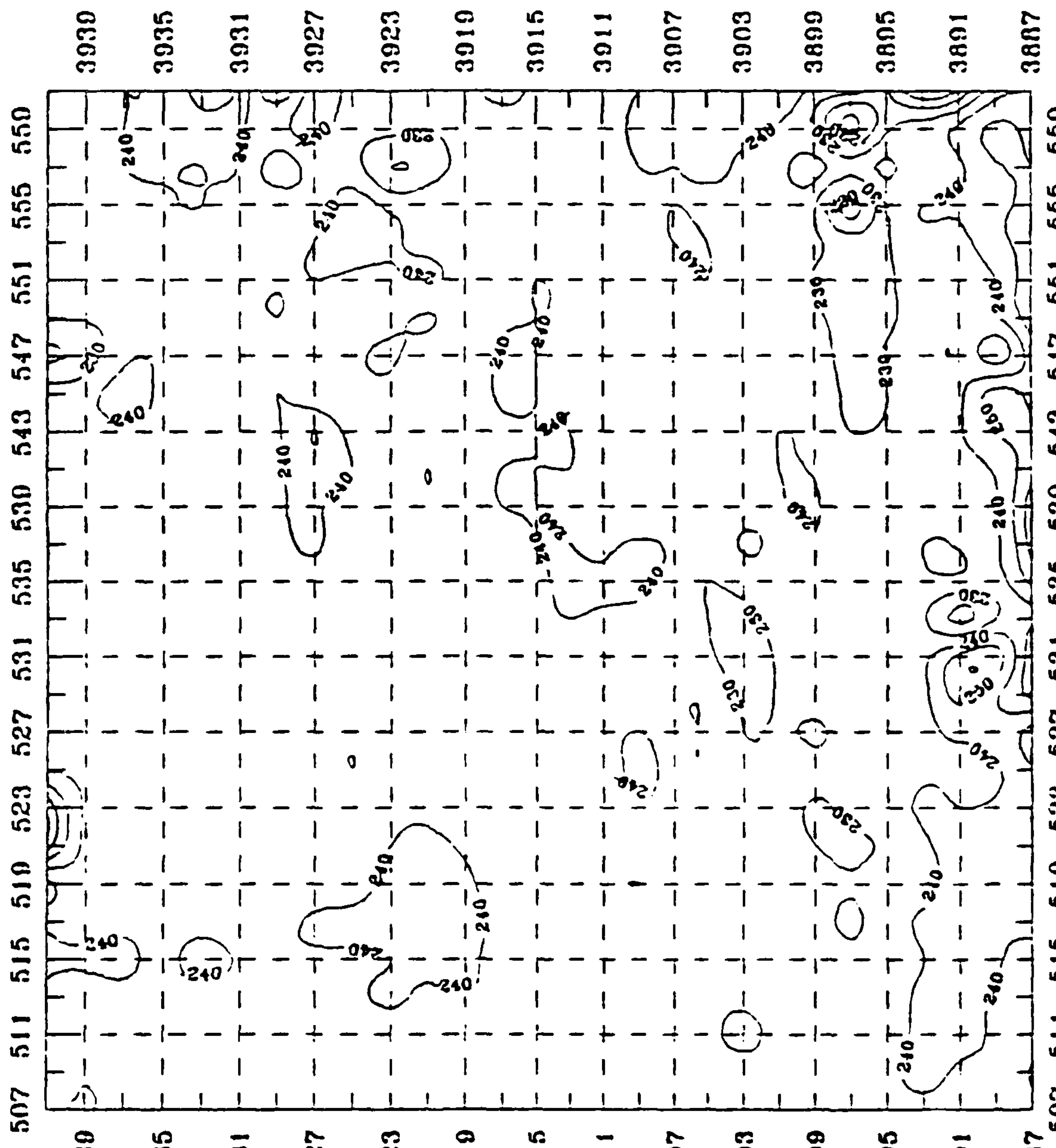


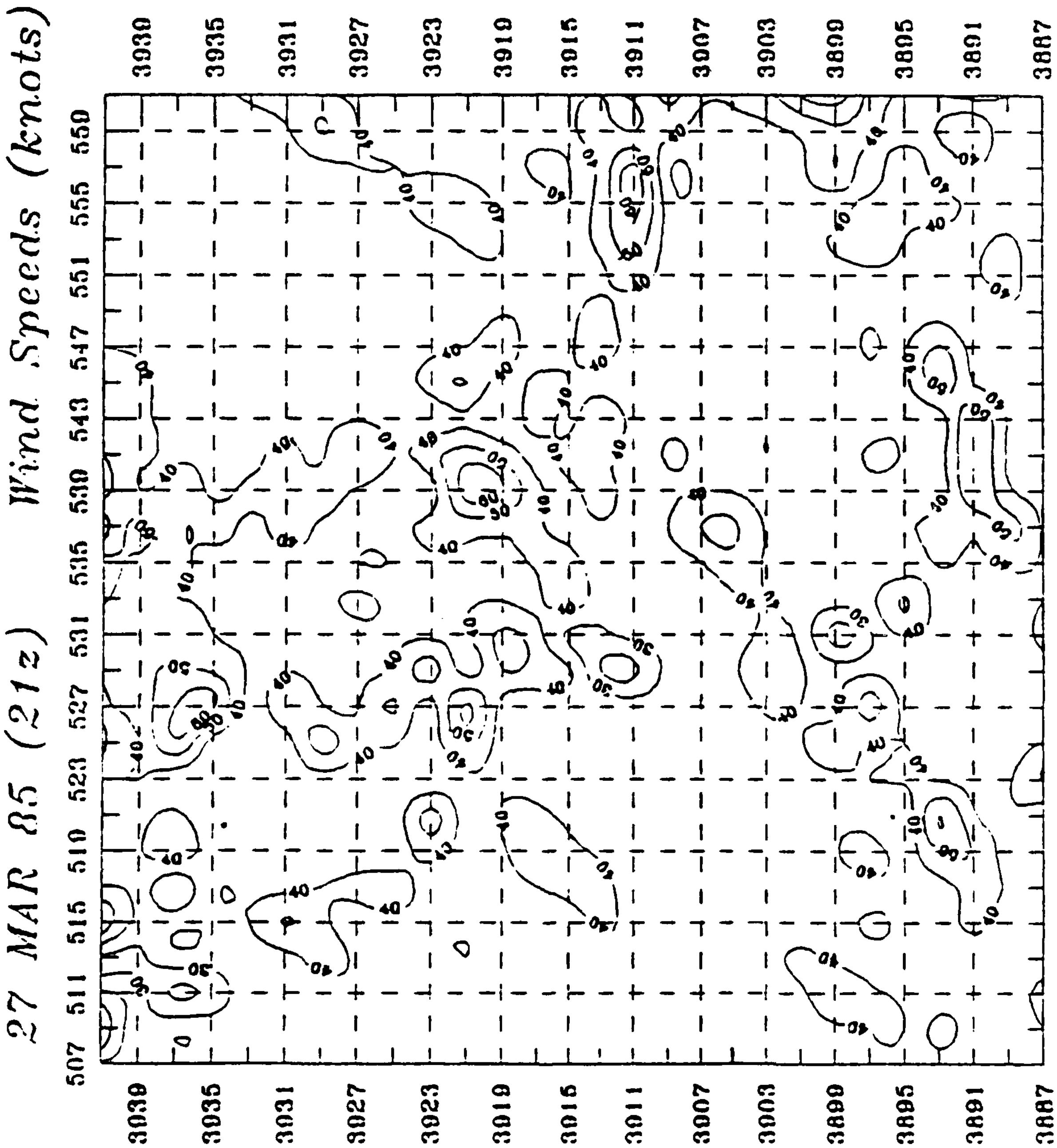
27 MAR 85 (09z) Wind Direction




27 MAR 85 (15z) Wind Speed (knots)
507 511 515 519 523 527 531 535 539 543 547 551 555 559
3939 3935 3931 3927 3923 3919 3915 3911 3907 3903 3899 3895 3891 3887

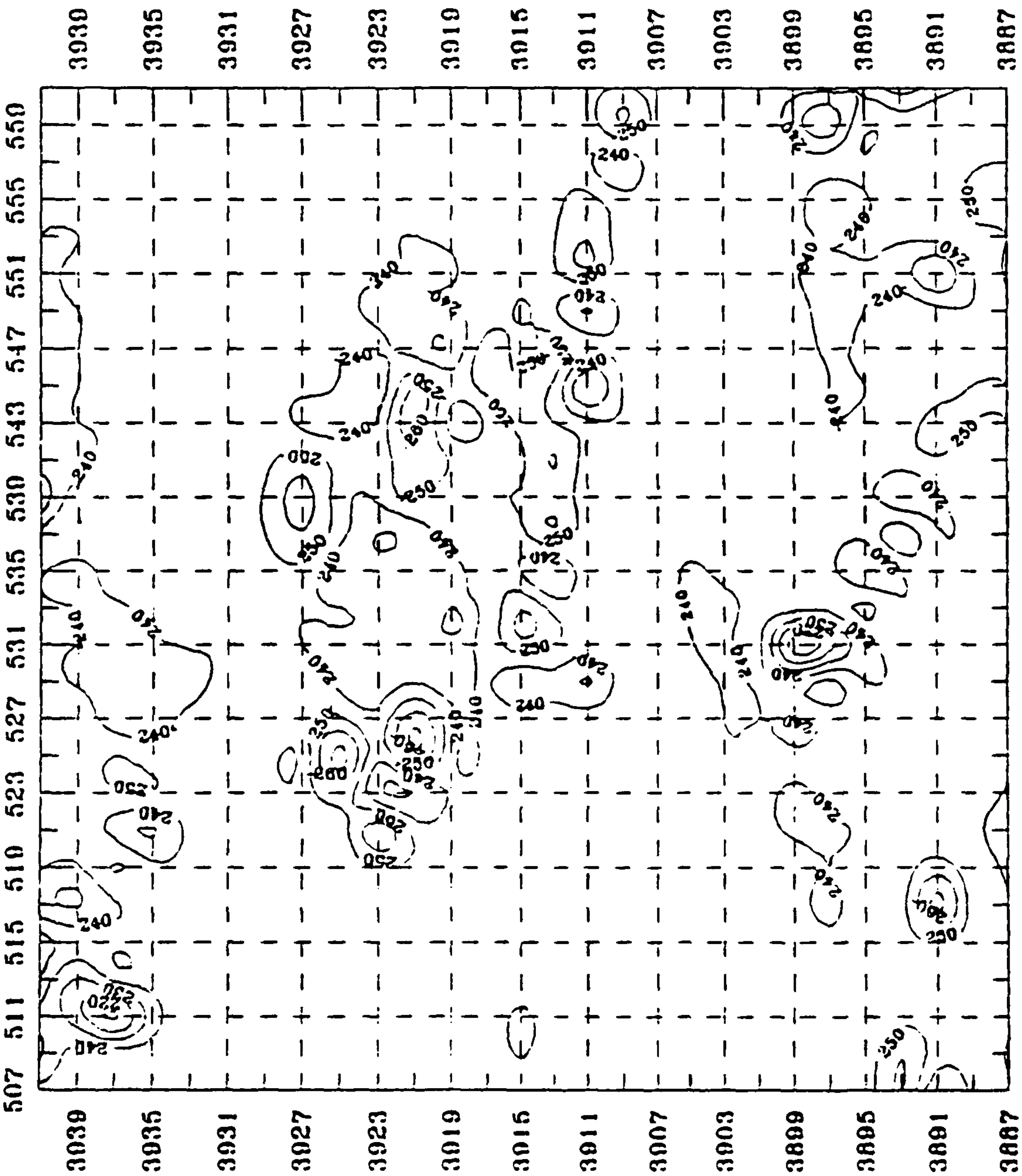
27 MAR 85 (15z) Wind Direction





27 MAR 85 (21z) Wind Speeds (knots)
507
511
515
519
523
527
531
535
539
543
547
551
555
559
3939
3935
3931
3927
3923
3919
3915
3911
3907
3903
3899
3895
3891
3887

27 MAR 85 (21z) Wind Direction

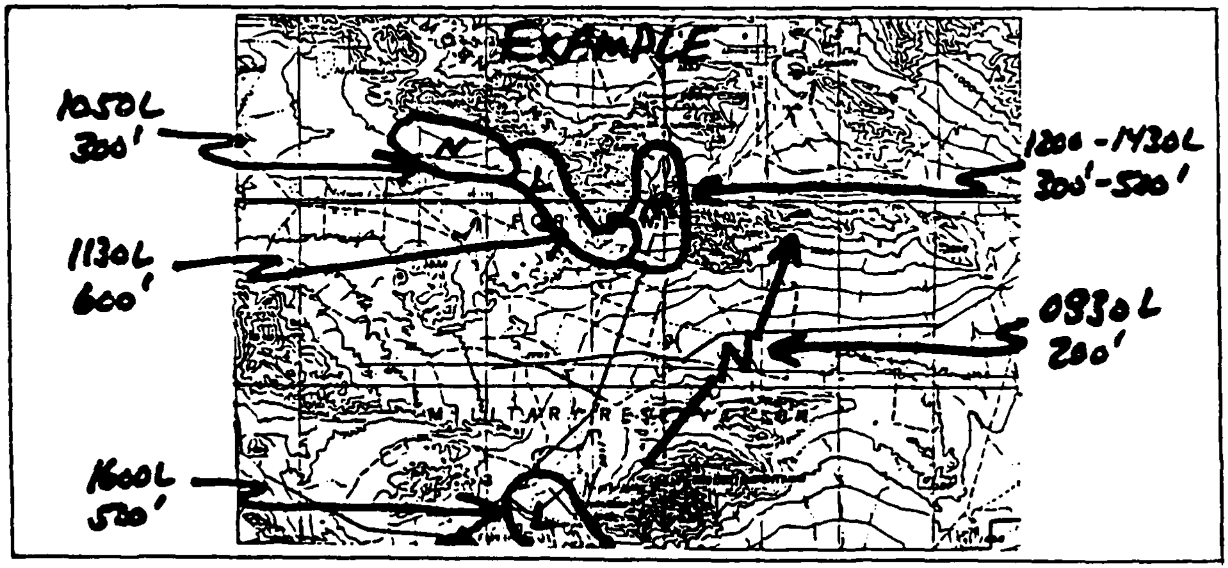


APPENDIX E. POST-FLIGHT TURBULENCE SURVEY

DATE____________________

POST-FLIGHT TURBULENCE SURVEY

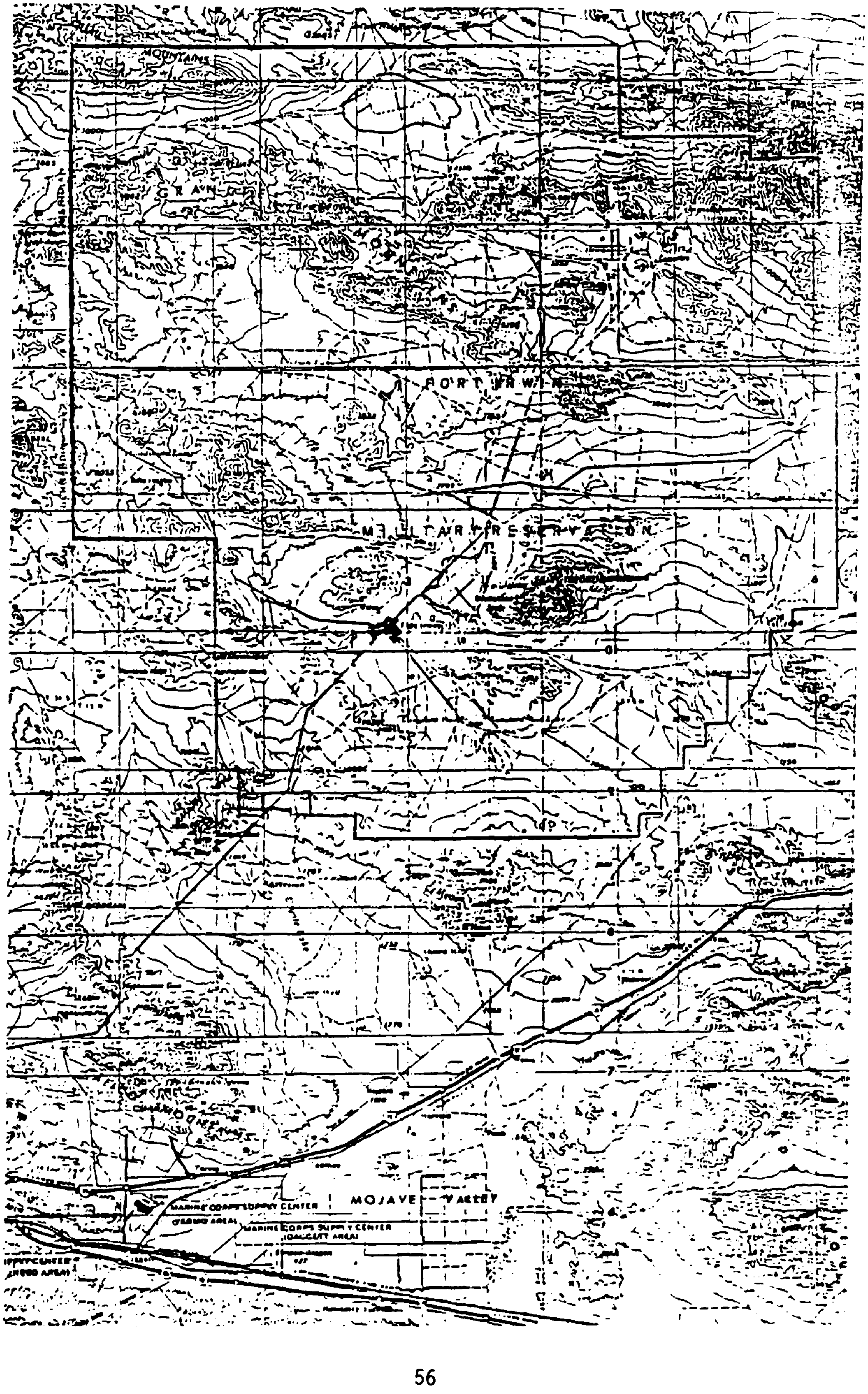
EXAMPLE



INSTRUCTIONS

ON THE MAP ON THE REVERSE, REPORT THE FOLLOWING: (NAME OR AIRCRAFT ID **NOT REQUIRED**) BE AS SPECIFIC AS POSSIBLE.

1. LOCATION.
2. TIME (LOCAL).
3. ALTITUDE ABOVE GROUND LEVEL (AGL).
4. TURBULENCE INTENSITY. USE STANDARD REPORTING CATEGORIES: None(N), Light(L), Moderate(M), Severe(S), eXtreme(X). PLEASE INCLUDE NEGATIVE (N) REPORTS.
5. SEE EXAMPLE ABOVE.


MOUNTAINS
FORT IRWIN
MILITARY RESERVATION
MOJAVE VALLEY
MARINE CORPS SUPPLY CENTER
MARINE CORPS SUPPLY CENTER
(DAGGETT AREA)

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